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The Proceedings

OF

THE INSTITUTION OF ELECTRICAL ENGINEERS

FOUNDED 1871: INCORPORATED BY ROYAL CHARTER 1921

PART A

POWER ENGINEERING

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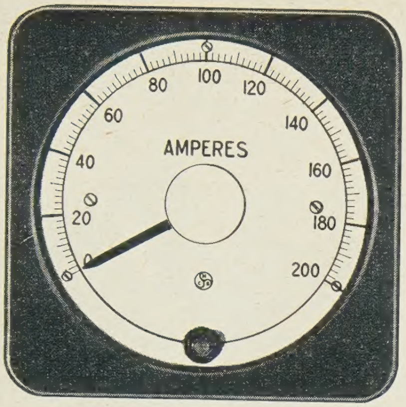
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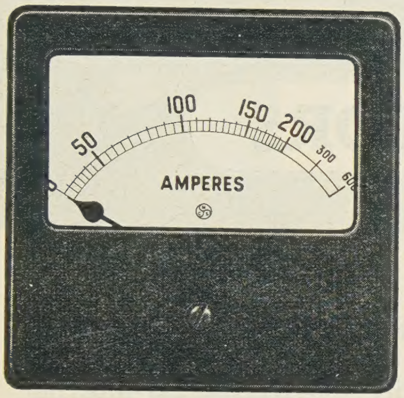
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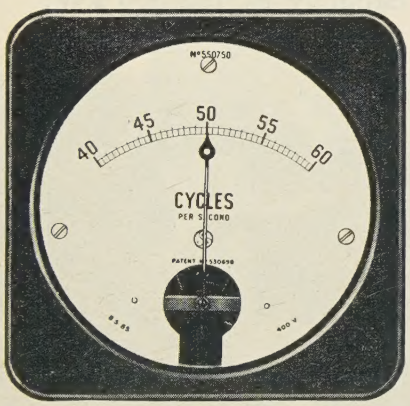
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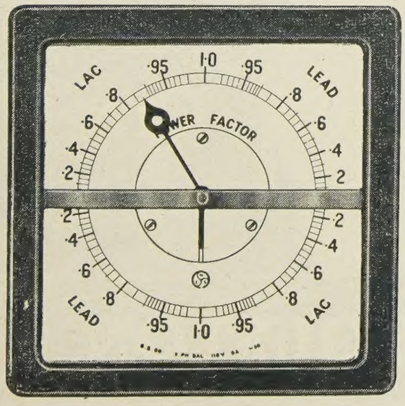
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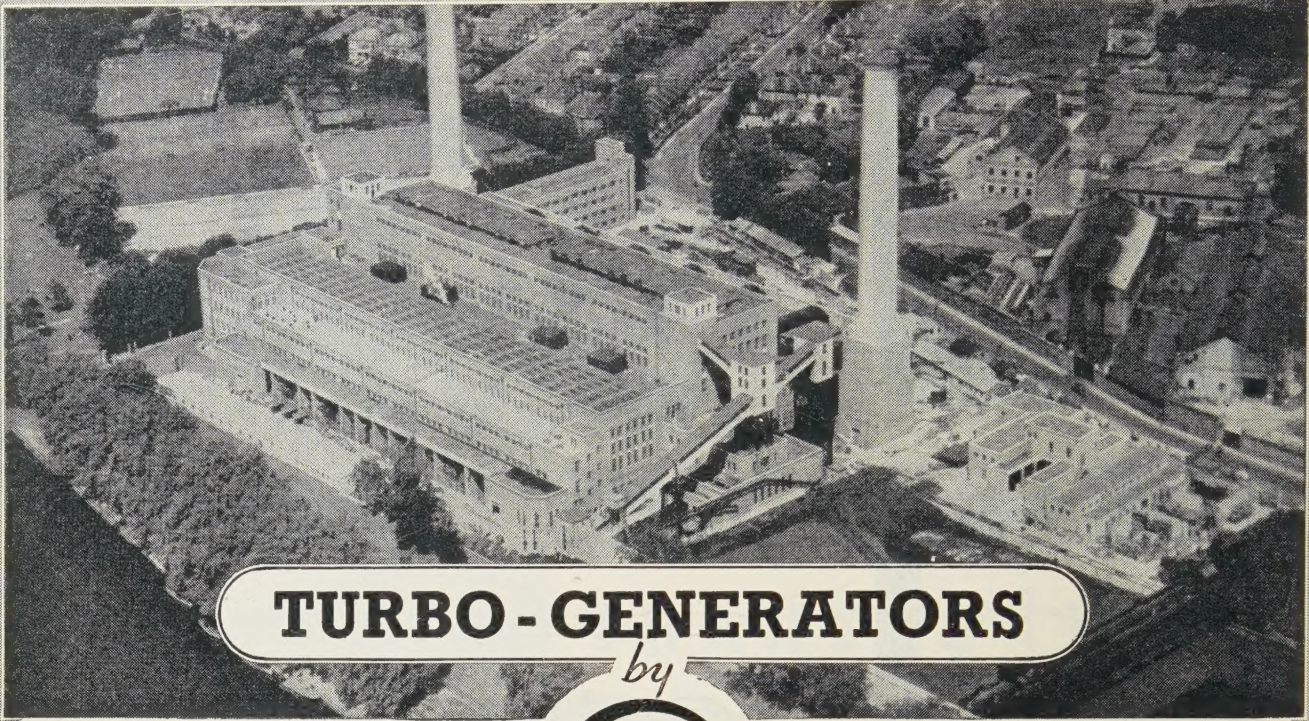

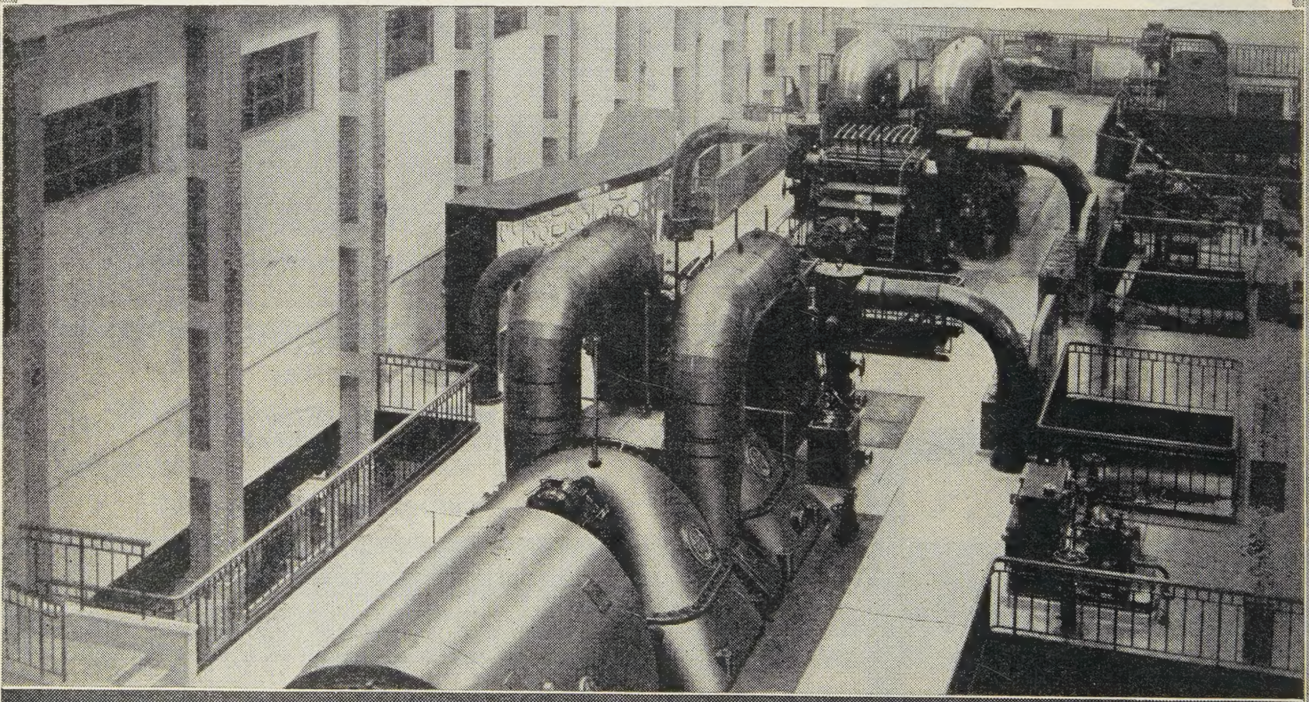

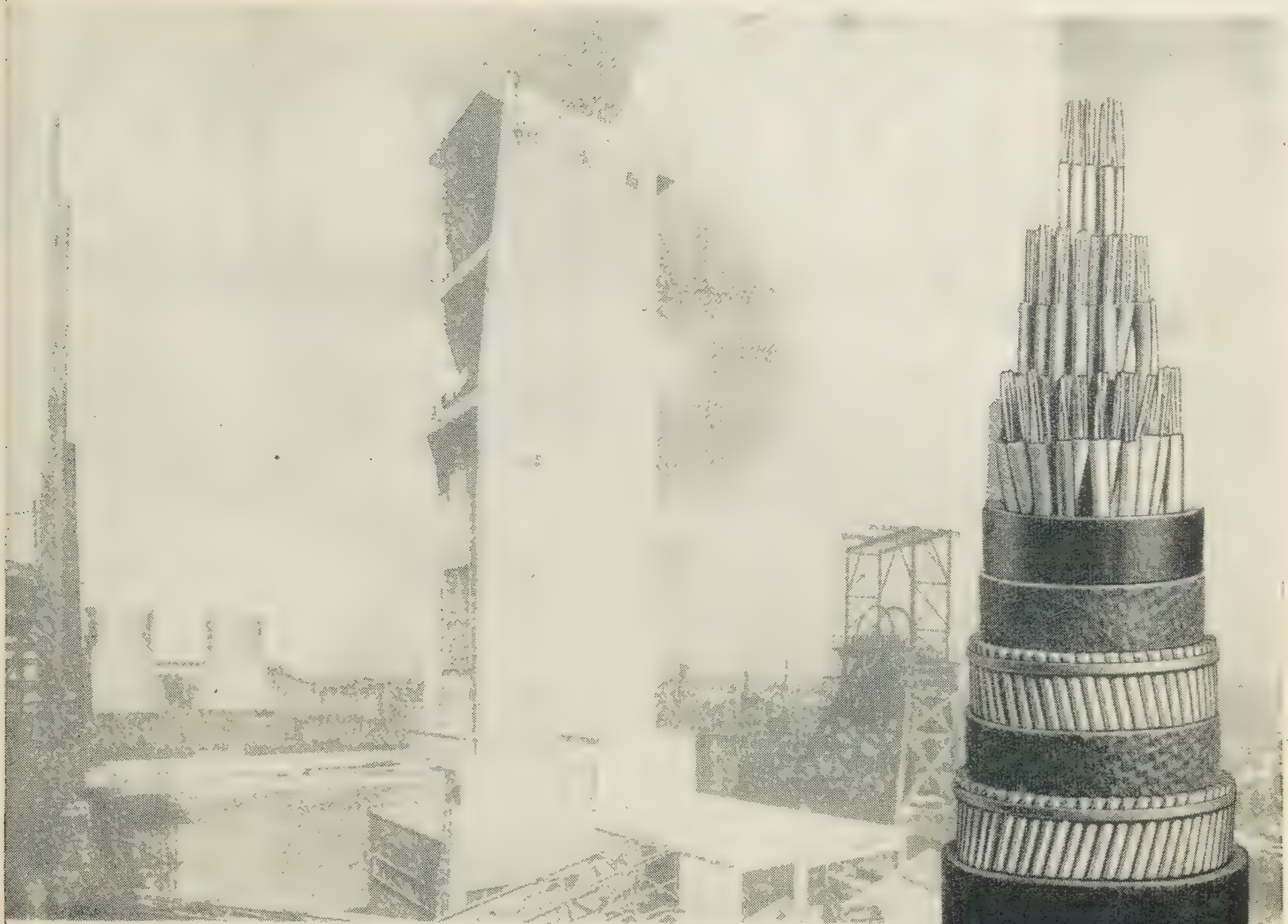

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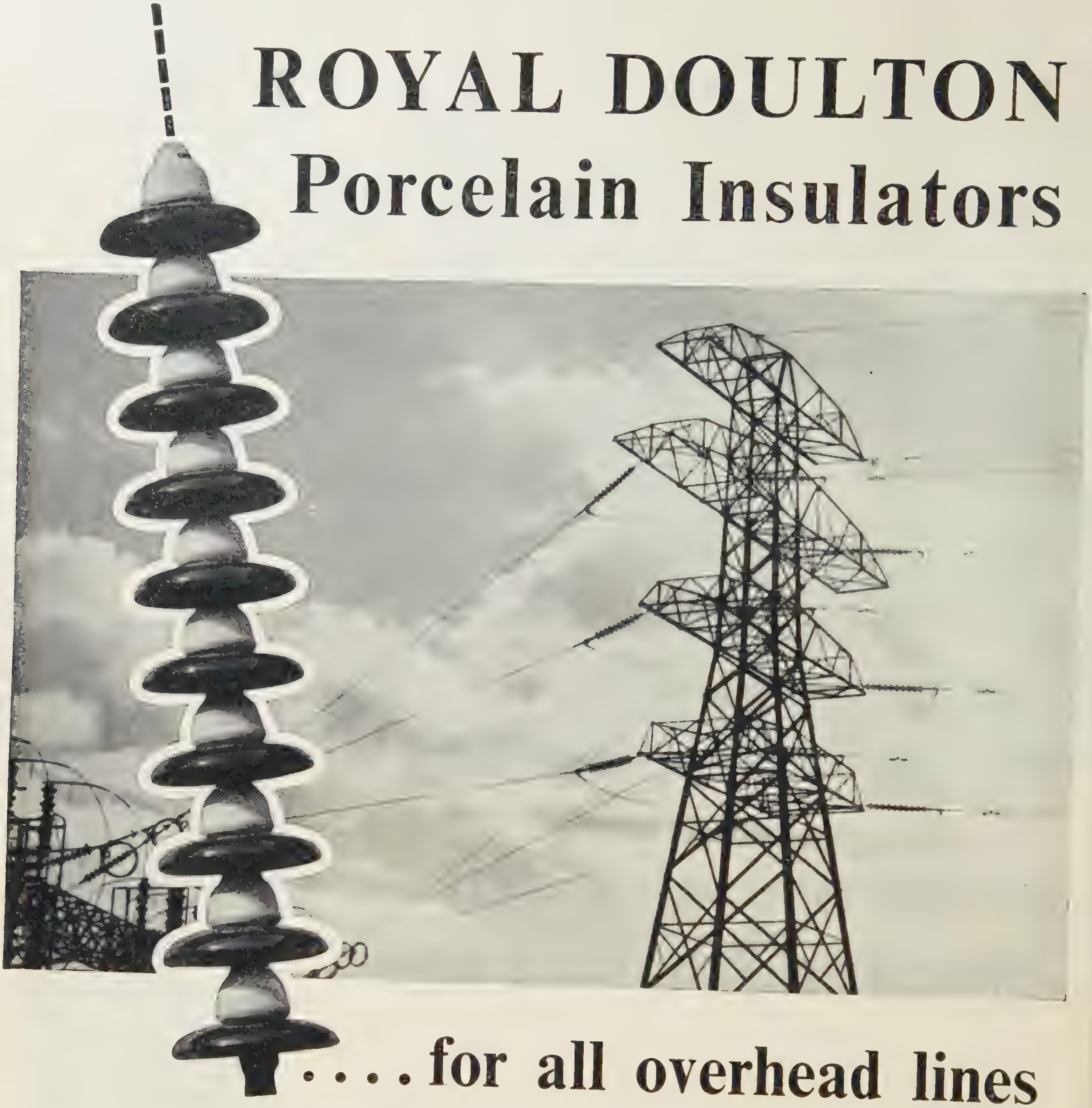

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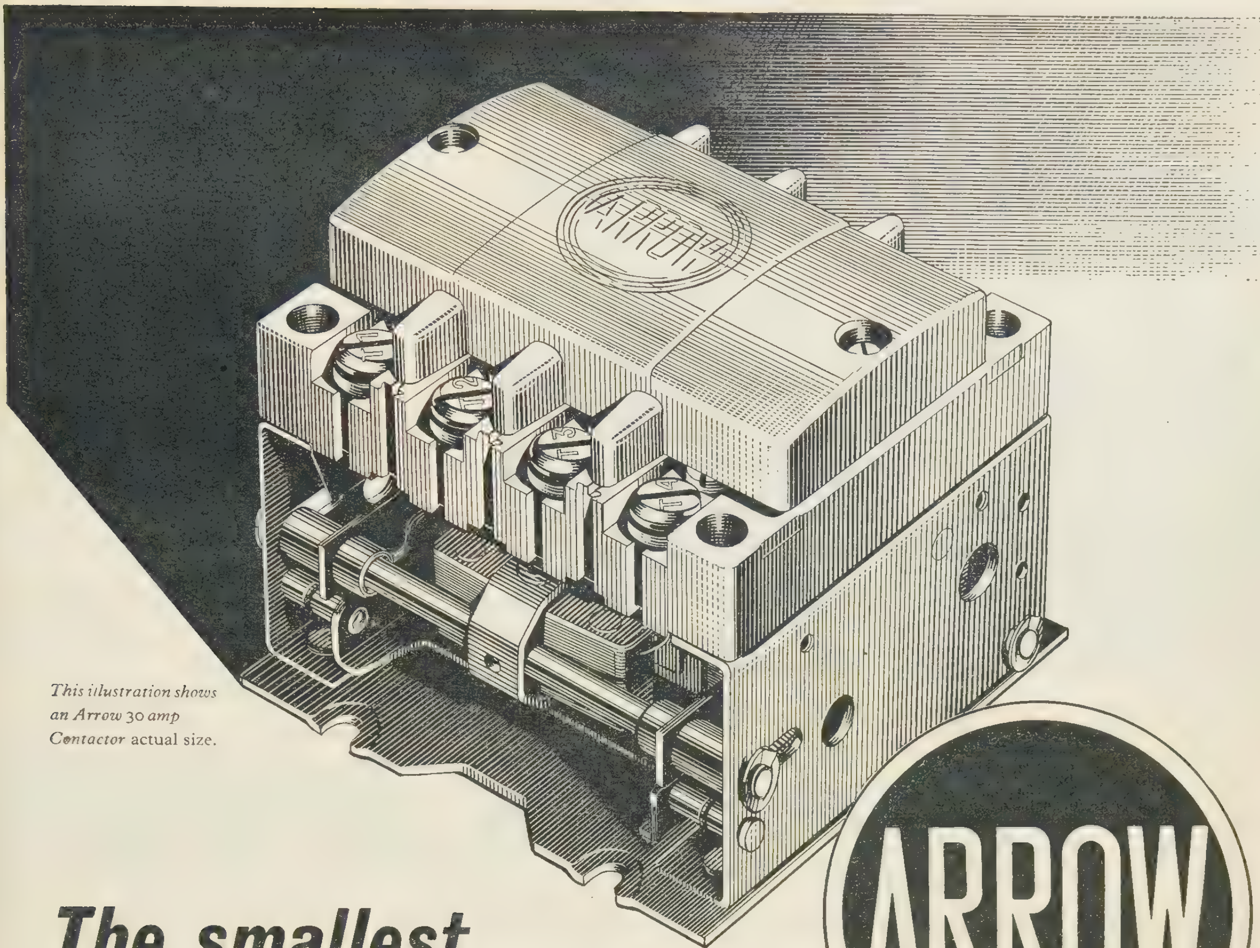

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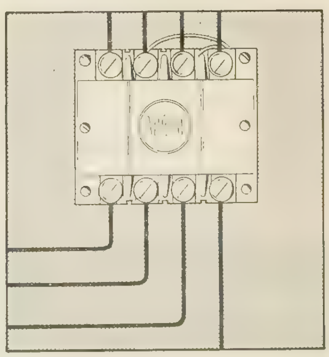

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1. *To Aid Employers.*

To receive inquiries from employers seeking the services of qualified professional engineers and to advise such employers, if required, as to the qualifications desirable for the particular vacancy.

To submit to employers particulars of persons registered with the Bureau, the qualifications of whom seem to fit them for the appointments.

2. *To Aid Members of the Institutions of Civil, Mechanical and Electrical Engineers.*

To receive applications for registration for employment from engineers, who by reason of their engineering qualifications are Corporate or Non-Corporate Members of The Institution of Civil Engineers, The Institution of Mechanical Engineers, or The Institution of Electrical Engineers (excluding Associates of The Institution of Civil Engineers); and to charge and receive such registration fees and appointment fees as may from time to time be determined by the Bureau.

To give advice generally in matters relating to the employment of professional engineers.

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Employers of professional engineers who have vacancies t be filled, are invited to notify such vacancies to the Bureau ar to furnish the following particulars:

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(5) Location of work.
(6) Could a successful candidate be assisted in finding suitable living accommodati locally?
(7) Does the post involve control of staff? If so, to what extent.
(8) Any other information which will assist in the selection of candidates.

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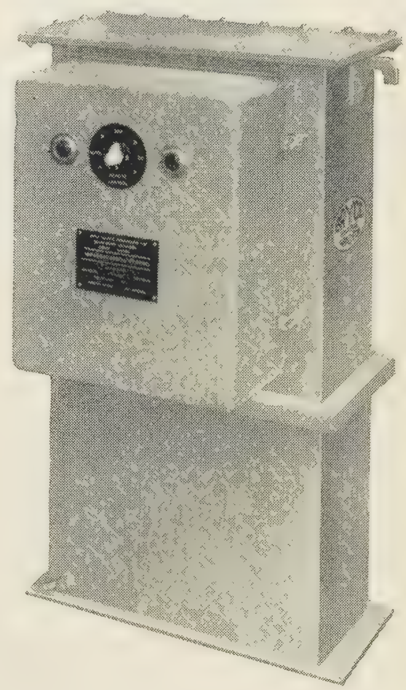

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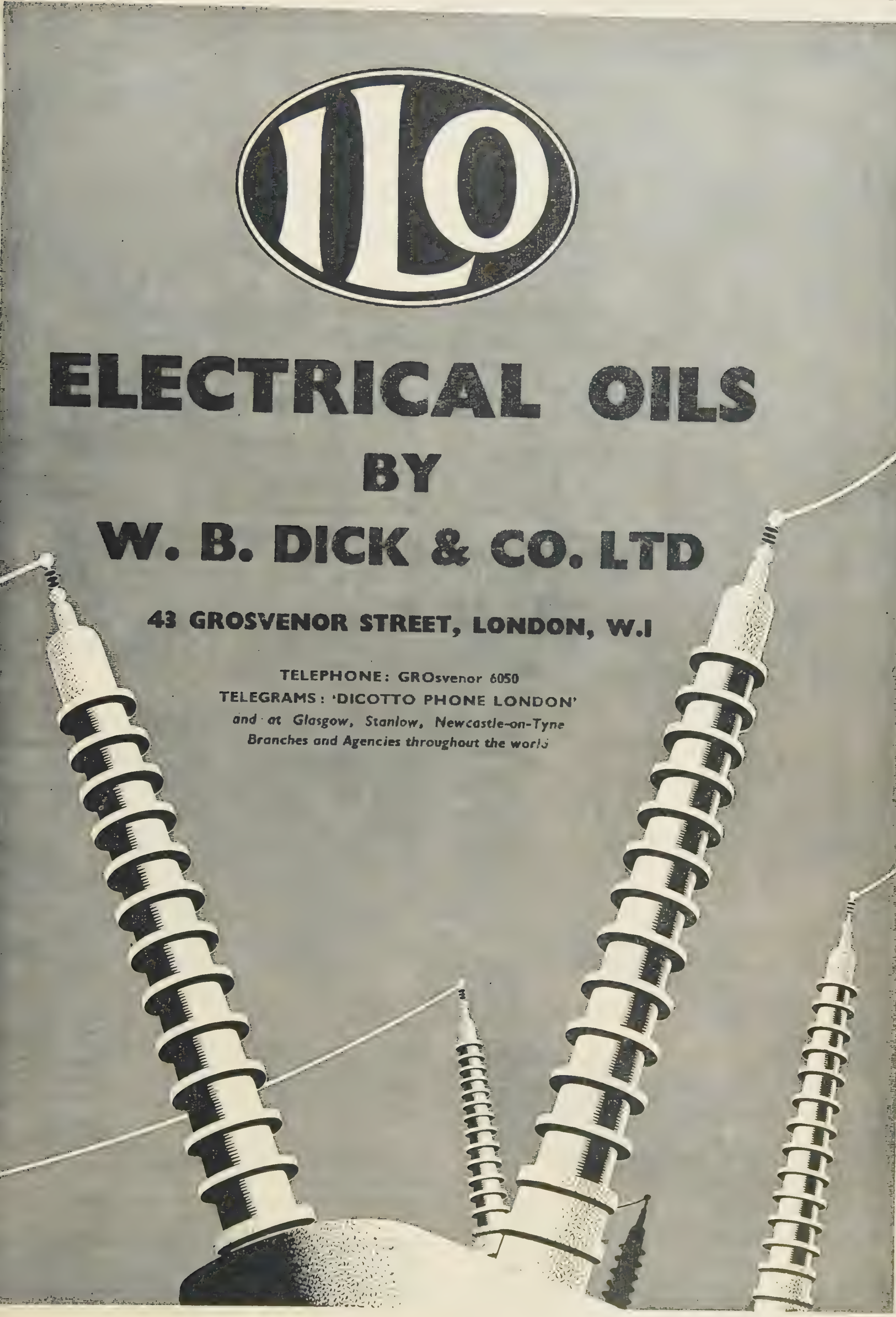
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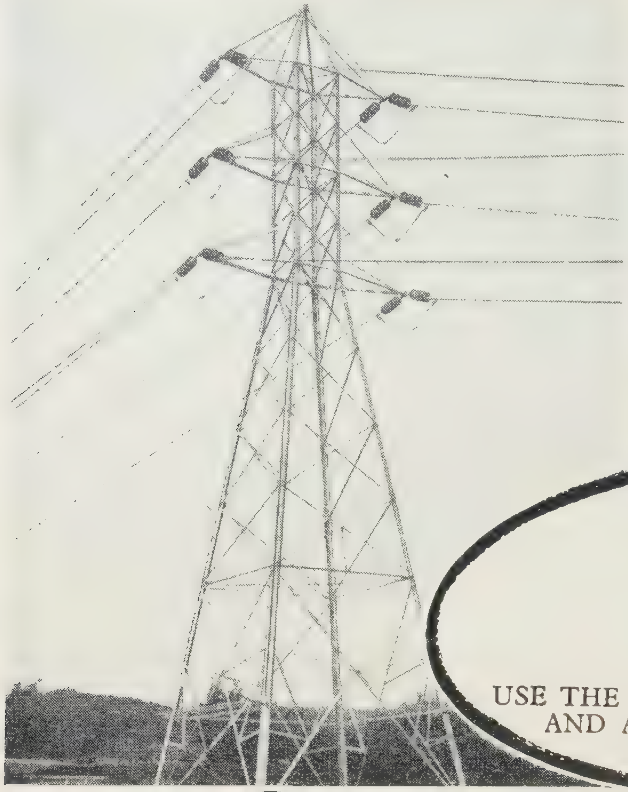

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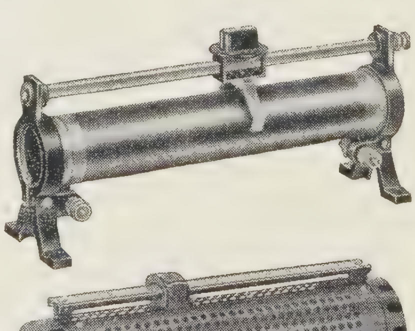

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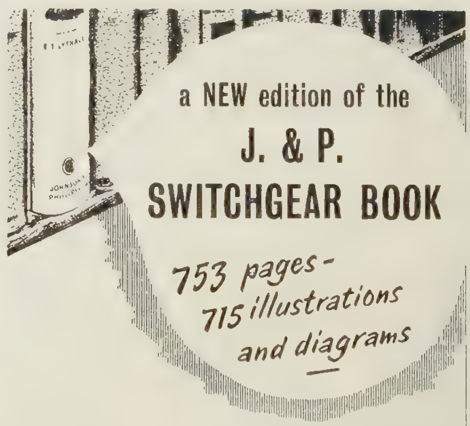

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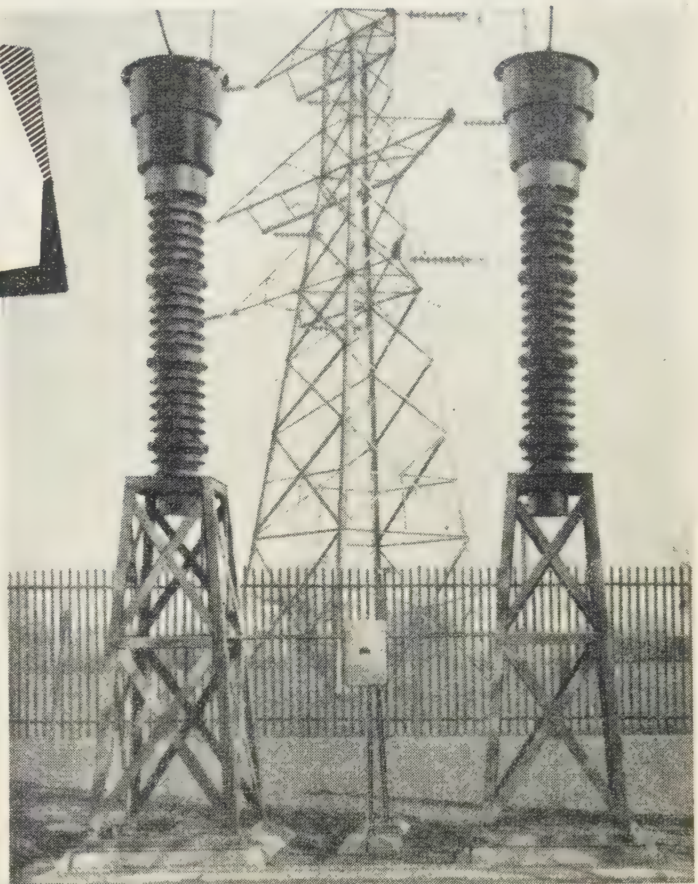

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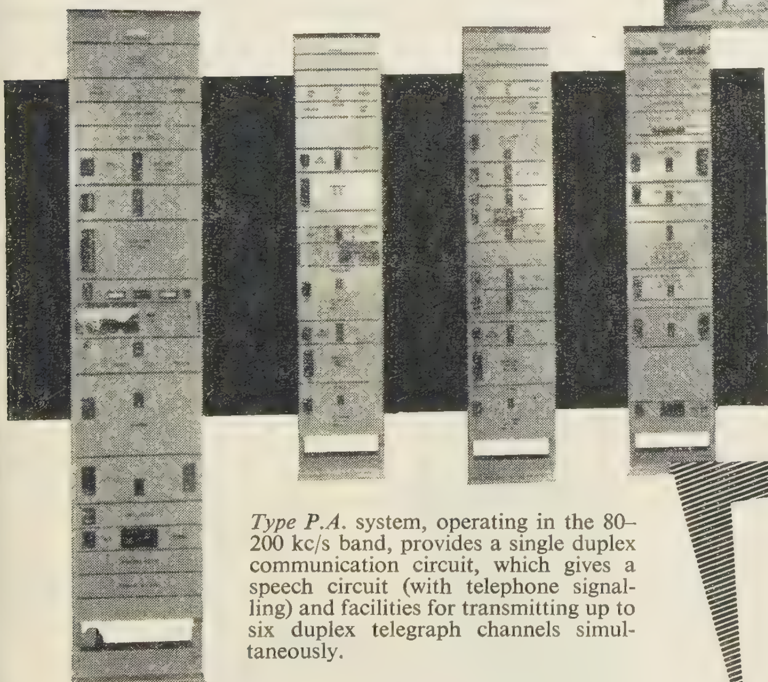

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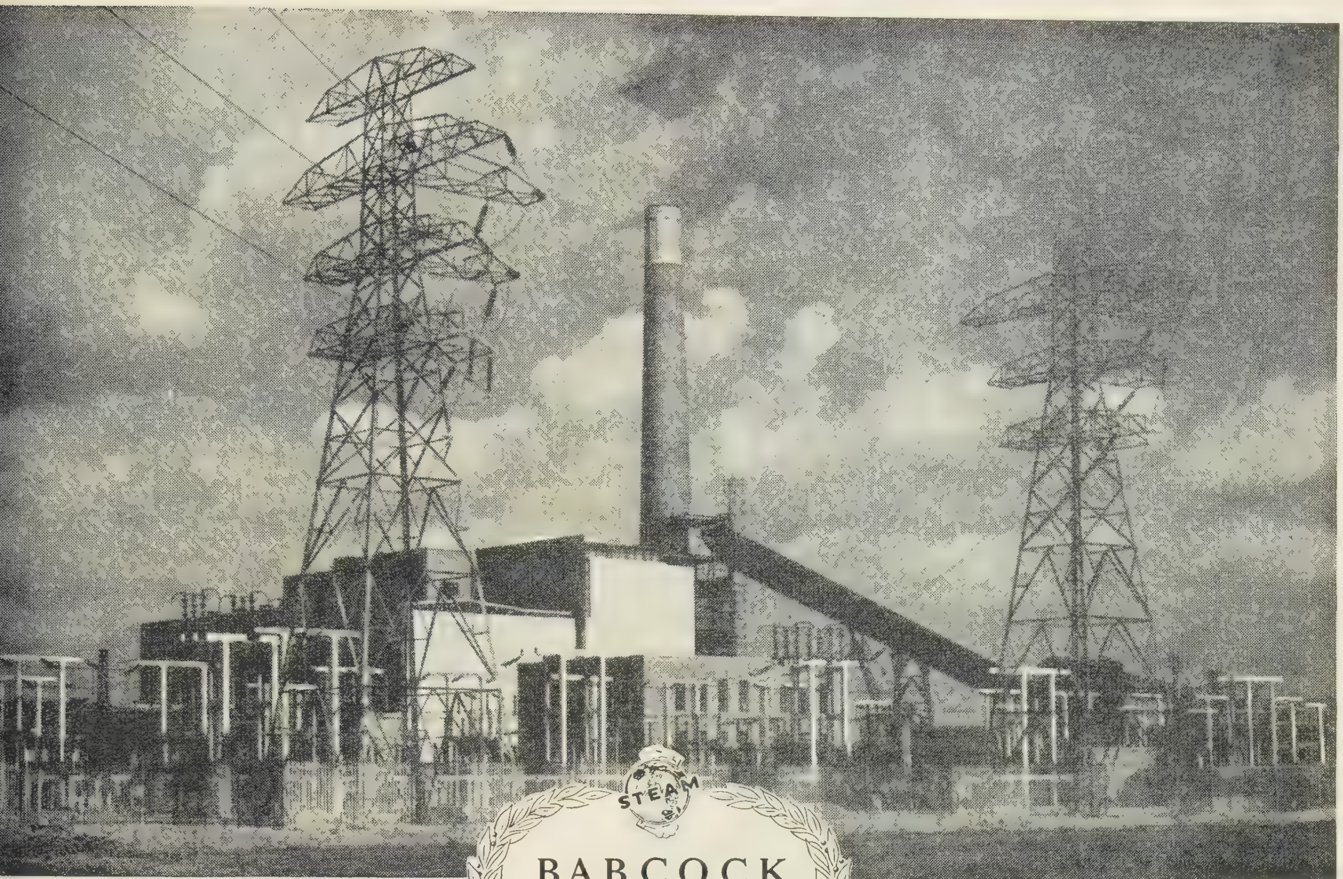

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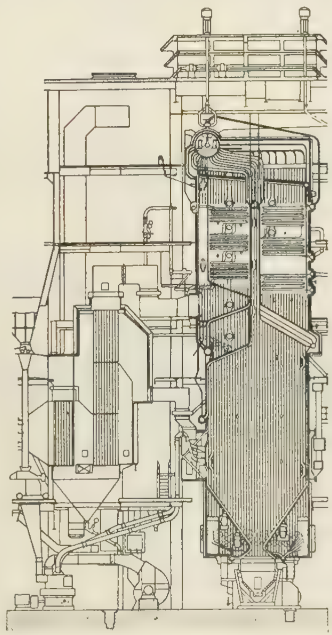

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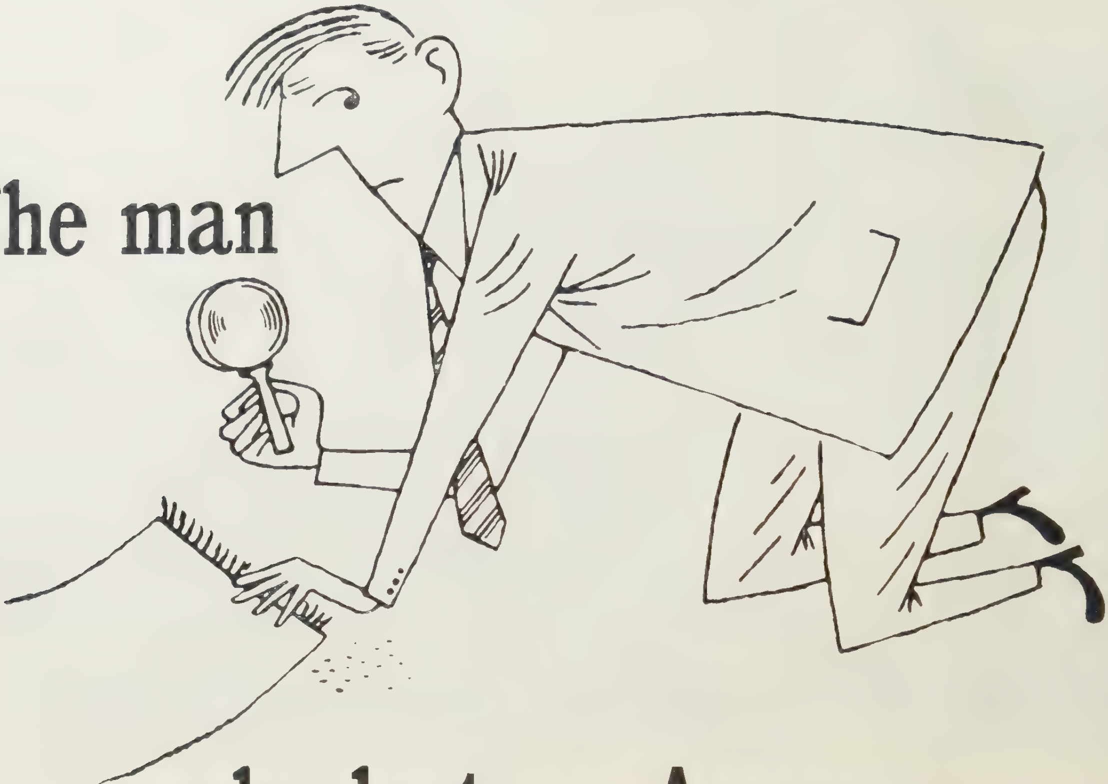

who lost an Ampere

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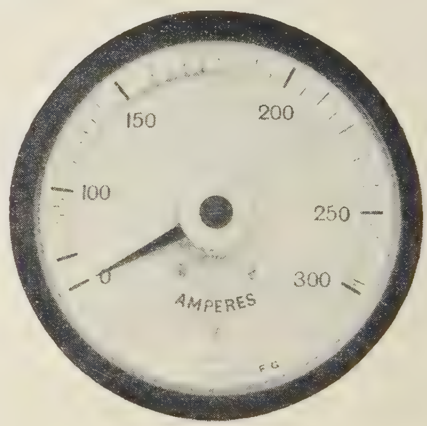

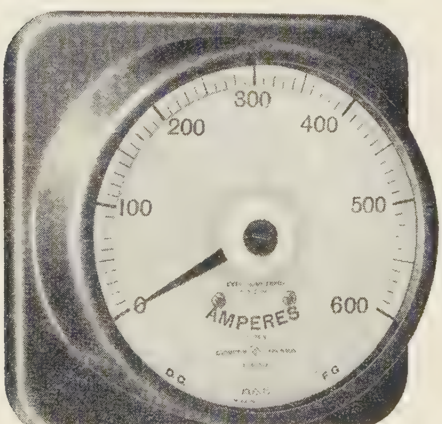

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Edited under the Superintendence of W. K. BRASHER, C.B.E., M.A., M.I.E.E., Secretary

Vol. 102. Part A. No. 1. FEBRUARY 1955

Paper No. 1804
Oct. 1954

INAUGURAL ADDRESS

By J. ECCLES, C.B.E., B.Sc., M.I.C.E., M.I.Mech.E., President.

(*Address delivered before* The Institution *7th October*, 1954.)

A sense of inadequacy serves to heighten my feeling of atitude to my fellow-members for having accounted me first nongst equals in The Institution for the period of one year. ly limitations are obvious and well known to many. As I and here somewhat in awe of those giants, my predecessors, me of whom adorn these walls and benches, I can but promise do my utmost to serve, whilst you may derive comfort from e thought that the wisdom of the Council, the knowledge of e Secretariat, and the restraining hand of tradition, will protect our interests. I thank you all.

The Institution has a membership of nearly 39 000, but mere umber is not strength, and the strength of this Institution rives from the fact that it knits together in common fellowship ose professionally engaged in the whole range of electrical gineering, from the practical application of well-established chnology to the translation of the newest theory into the techcal marvels of our age.

To do so, there must be wise and energetic leadership with the aximum practicable degree of devolution of responsibility to e Sections, Centres and Sub-Centres. That this is achieved is tribute to the enlightened guidance of Mr. Brasher and his aff, and to the reservoir of managerial experience distilled rough the deliberations of your Council. The manner in which e Sections and Centres discharge their duties, and seek to omote the highest interests of The Institution and the technical ell-being of its members, is a source of constant admiration.

Through the papers that are published, with or without disssion, The Institution seeks to include in its *Proceedings* a mplete record of technical progress in all branches of electrical gineering. Many of these papers are necessarily of a highly ecialized and mathematical nature. Whilst recognizing that a gh degree of specialization is essential to economic success and at the tendency may increase, it is important to ensure that the neral practitioner and other specialists are kept informed of e trend of events in fields other than their own. To this end, is greatly to be hoped that more members will find time to esent papers of a general character on the current techniques their own spheres.

As I hope to show, we are faced with the prospect of an everpanding range of research and experiment in difficult fields, d if we are to succeed it is imperative that the volume and ality of technical education and training should be stepped up. s the privilege and the duty of The Institution to offer informed vice on this matter to those whose responsibility it is to decide the form and extent of the educational facilities to be provided. This duty is being discharged.

One of the things causing concern is the inadequacy of the intake of students and juniors to the electrical engineering profession. Insufficient schoolboys are imbued with scientific insight and knowledge of the part that science must inevitably play in securing an acceptable existence in an industrial country. Too many are unable to pass the university entrance examinations. If this defect should stem from lack of appreciation by headmasters, housemasters and careers masters of the indispensable necessity of scientific education, it calls for immediate remedial action at those levels. If the teaching of science in schools cannot be improved and extended, the universities may have to consider the selection of entrants more on potentialities than on detailed scientific knowledge, and themselves teach science from an earlier stage. Character and an inquiring mind may be a better foundation than very early knowledge of Ohm's law.

A further thought on this may be worthy of record. It is a fact that each generation of technologists has to learn its technology from the beginning. There is no way of starting where the other man left off. Each must plod through the ABC of the subjects he elects to study. To simplify this process should be a duty of educationalists, and how better might this be started than by simplifying the units in which basic quantities are measured? The rationalized M.K.S. system of units has been recommended as an international standard by leading authorities, and it would seem that the time has now come when this simplification could be used exclusively in textbooks and academic courses.

Although there is no restriction upon the subject-matter of an Inaugural Address, it will not have escaped notice that almost invariably each holder of this office has, quite naturally, chosen to discuss in his Address some aspect of the work upon which he is engaged.

I am an electrical power engineer and, fortunately for you, though unhappily for me at this moment, Sir John Hacking in his memorable Address three years ago, and more recently in his Presidential Addresses to the British Electrical Power Convention and to the Junior Institution of Engineers, has given very full accounts of the immediate past and middle-distance future of electrical power engineering in this country.

One could attempt to dot some of the i's and cross the t's of what has already been written. The story of the 275-kV Grid could be brought up to date. Then, too, there is the proposed cross-Channel connection linking Britain with the European mainland across a 26-mile stretch of turbulent sea with rocky

Mr. Eccles is a member of the British Electricity Authority.

foreshores and an uneven bottom reaching a depth of 216ft at its lowest point. Again, there is the continued story of endeavour and achievement in the field of power generation in which the equivalent of six modern power stations are fully equipped each year, thus bringing into use some one and a half million additional kilowatts of electrical generating capacity in Great Britain alone. On the utilization side there is a human story in the manner in which electricity is spearheading the drive for food production and arresting the depopulation of the countryside, and there is much of technical interest in the means whereby annually over 10 000 farms and three times as many rural dwellings are receiving supply in this country for the first time.

It would have been possible to develop and arrange thoughts on these and other aspects of electrical power engineering, but inevitably they would have had to be of a detailed character and so were better dealt with in discussable papers.

In this Address, therefore, I wish, with your permission, to depart a little from tradition and offer some observations of a very general character on the long-term past and future of power engineering. Much of what I propose to say will be familiar to many members, for never before has there been such an awareness of the consequences of continued exploitation of known natural sources of energy or so much written about the need to discover and utilize new ones. From the initiated I crave indulgence.

Before delving into the past or peering into the future, it may be well to consider what it is the power engineer seeks to do and why it is necessary to have him around at all. The function of the power engineer, as I understand it, is to give man command over Nature by releasing her great storehouse of energy and presenting it in forms and quantities that, at one end of the scale, enable him to achieve the otherwise impossible, and at the other, enable him to gain a livelihood without undue physical exertion. Between these extremes he provides, in a great variety of ways, the means whereby man may live a fuller life, or if he chooses, effect his own destruction. To-day we accept the benefits as a matter of course, and realize their significance only when they fail to appear, but let us pause for a moment to discuss their magnitude and their effect upon our mode of living.

Each year in this country we consume about 200 million tons of coal. It is probable that half of this is used to produce mechanical and electrical power. Taking a realizable efficiency of conversion from coal to usable power at the point of application, it is easy to show that 100 million tons of coal used in this way will do the work of at least 750 million unaided men working a 44-hour week for 50 weeks. The population of this island is rather less than 50 million, and hence by the conversion of this amount of coal into work we have endowed each man, woman and child with fifteen slaves to do their bidding. These slaves propel trains and trams, operate cranes, turn lathes and boring mills, whirl vacuum cleaners and washing-machines and actuate the myriad host of power-driven appliances on which our civilization depends.

Oil provides another set of slaves to propel cars, buses and lorries, tractors and bull-dozers, ships and aircraft, and a calculation of the same kind shows that the present consumption of liquid fuel in this country provides the equivalent of a further five slaves for each living soul in Great Britain. These latter have to be purchased in, and transported from, foreign lands, but, this done, the whole platoon requires neither food nor raiment, and all we have to do is to provide their working tools and ensure that they are usefully employed.

The conversion factors used may not be quite accurate, but they are of the right order, and the result illustrates our utter dependence, in the 20th century A.D., on the sources of power in nature brought under control and regulated for our benefit by the power engineer.

How then has it come about that each of us has to depen upon 20 inanimate slaves to maintain his present standard mobility, comfort and leisure? For how long has this bee going on, and what are the chances of its continuance? The are some of the vital questions of our age, and in attempting answer them let us go backwards in history a little way.

Some geologists compute the age of the earth to be about 3 00 million years. Nine-tenths of that period passed without an event of significance to power engineers until about 300 millio years ago, in circumstances which we can only conjecture, the seems to have occurred upon this planet a condition, or series o conditions, conducive to luscious vegetable growth over larg tracts of its swampy surface. Vegetation grew, decayed, wa reborn, and decayed, repeating its life cycle for perhaps tens o millions of years, until there was built up stratum upon stratum o hydro-carbonaceous matter.

Times changed, the climate altered, there were violent interna explosions with consequent disturbance of the earth's crust, dr land became the sea-bed, the valleys were exalted, the mountain were brought low, there were long periods of snow and ice, an never again have there been repeated in nature conditions s conducive to an accumulation of her precious hydrocarbon store To this event, or series of events, we owe the coal measures an the oil wells which to-day provide over 85% of the world's fue This garnering of nature's harvest being over, there is nothing o significance to relate until beings resembling man made thei appearance about a million years ago. We know little that i not somewhat speculative about the evolution of man, befor the period of recorded history. It is thought, however, that million years ago he knew how to initiate and control fir and it would seem that his progress since then has been con ditioned as much by the state of his technology as by an other single cause. For a very long time men remaine gatherers as distinct from producers. They were content t take what nature provided and use it as best they could. Late they assumed a more active role and endeavoured to improv upon nature by tilling and fertilizing the soil, using domesticate animals for work and food and fashioning tools of stone an metal to increase the range and usefulness of their endeavours It was in this latter phase that the demand for fuel grew apace Wood was required for warmth, for cooking and for smeltin metal, and whole districts were deforested by burning for n other reason than to provide wood-ash as a fertilizer. Larg areas in India, China and other countries were devastated in th way, and when in these areas crops failed through lack of furthe enrichment of the soil, the population was decimated by starva tion, and so the culture died that had blossomed in the previou age of plenty.

The record of these early civilizations seems to show that a improvement in technology encouraged an increase in populatio which overshot the capacity of the reigning technology to fee and to clothe, with the result that, in the exercise of that stronges human instinct—self-preservation—man with his limited know ledge unwittingly cut off the branch on which he sat. Thus was that lack of knowledge of what nature held in store, and lac of knowledge of how to use efficiently the known resource caused cultures of high rank to wither and, in some cases, t vanish from the earth.

However, the pattern was not even and, in some areas, im proving supply technology, aided by slave labour, was able t meet the increasing demand for long periods, By 10000 B.C men knew how to make bricks, by 6000 B.C. they began to ta the fossil fuels, beginning probably with the most accessib deposit, asphalt. Earthenware vessels were made as early a 5000 B.C. The Chaldeans were skilful metal workers by 4000 B.C

imestone was calcined and enamelled pottery made in Egypt nd Babylon by 3000 B.C. Asphalt was used in the building of ie Pyramids and for waterproofing the walls of Jericho. In abylon, roads were built by setting stones in asphalt, a practice evived by J. L. McAdam some 2 500 years later.

About 1000 B.C. the Chinese were using natural gas for fuel nd lighting, which they procured from wells 3 000 ft deep and ansmitted in bamboo pipes. According to Herodotus, an oil ell was working on the island of Zante in 400 B.C., the lighter actions being separated by stretching a hide over a cauldron of oiling oil and wringing out the condensed liquid.

The earliest recorded use of coal is 1100 B.C. in China. At nat time, Chinese technology was sufficiently advanced to enable nem to produce saltpetre, arsenic, mercury, vegetable oils, paper, ugar, printing and gunpowder. The first use of coal outside China was probably in Greece, and there is evidence that coal was nown and used in Britain before the Roman occupation.

These apparently isolated but perhaps not unconnected xamples of technological progress coincided, in some cases, vith quite advanced civilizations, but it may be significant that lmost invariably an improvement in supply technology was ccompanied by an increase in population and by an arrogance r indolence in the governing body, which formed the seed-bed f decay. In this respect, things came to a head round about 00 B.C. In 538 B.C., Belshazzar was slain on the night of the andwriting on the wall and the Babylonian empire came to n end. In China, industrial progress ceased with the full owering of the Confucian philosophy, and in India the caste ystem withdrew all intellectuals from the industrial crafts. Greek industrial progress died with Alexander the Great.

These events and others ushered in a period of two thousand ears of technological stagnation in which, whilst fuel was still sed for heating, little further progress was made in establishing nan's command over nature. This period includes the Greek nd Roman civilizations, which made little attempt to revive uel technology. Greek intellectuals scorned those who tried to urn technical theory to practical advantage, and, though the Romans invented the water-wheel and the concave mirror for oncentrating solar heat, their source of energy was almost vholly that of slave labour and animals right to the end. What vas needed was the discovery and application of means to ugment man's energy and improve his transport. The hoenicians had used the force of wind in sailing ships since 000 B.C.; Hero of Alexandria came near to converting heat into vork; the Romans used water power and the Chinese had used ie explosive force of gunpowder. But no one knew how to arness nature continuously on the scale necessary to suit the rowing human need.

It would be wrong to suggest that nothing happened anywhere uring the Dark Ages. At the end of the Roman occupation, ritain experienced a political setback, but with the gradual mergence of more settled times the demand for fuel outstripped ie current rate of vegetable growth and the countryside was eing steadily denuded of its forests. Long before this, coal ad been discovered as an outcrop and its value as a fuel was nown. It was not a popular fuel, and in the reign of Edward I decree was made compelling "all but smiths to eschew the bnoxious material and return to the fuel they used of old."

Thus we arrive at the 15th, 16th and 17th centuries A.D., with cience and technology slowly awakening and facing the prejudices iat had become entrenched in men's minds, without opposi- on, during their long period of hibernation. It was in this etting at the very end of the 17th century that an Englishman, homas Savery, invented the first successful steam engine and iowed how heat could be converted into work. By means of iis engine, improved by Newcomen and Watt, there was tapped an enormous reservoir of energy stored in the coal measures for 300 million years. The amount of power that was there for the taking seemed unlimited and the scale of human achievement made possible by this new mechanical aid dazzled the imagination. It was natural that the first applications of steam engines should be for pumping and winding at coal mines, but, once this main source of power energy had been made secure, their use became general. In 1827, the first steamship crossed the Atlantic to the New World, and in 1829 the first steam-driven railway locomotive was in operation. In 1884, Charles Parsons invented the first practical steam turbine, which so raised the sights in size and efficiency that to-day single machines are being designed for an output of 200 000 kW using only three-quarters of a pound of coal per kilowatt-hour.

Contemporary with these events in the realm of steam, work was in progress on the design of machines in which controlled explosions of oil or gas could be translated into continuous mechanical power. The result was the internal-combustion engine, which, apart from many useful fixed applications, completely revolutionized the mode, range and speed of transport. The first motor-car using this engine took the road in 1885, and the first aeroplane left the ground in 1903.

Prior to the emergence of most of these applications, Michael Faraday had discovered and demonstrated how a new and more versatile form of power could be made available. As every member of this Institution is aware, it was at the Royal Institution, London, on the 29th August, 1831, that Faraday first demonstrated the basic principle of electromagnetic induction now used in every electric power generator throughout the world.

The result of these epoch-making inventions and discoveries has been that man, after surviving for nearly a million years on the gifts of nature as they were currently produced, and being frustrated from further development by the inadequacy of his technology, has in some parts of the world during the past 250 years developed a method of living that transcends everything hitherto achieved, but is largely dependent upon the use in enormous quantities of natural energy stored in a bygone age.

Earlier in this Address, I suggested that the present use of energy was equivalent to the service of twenty slaves for each person on this island, and I posed questions on the chances of this state of affairs being maintained and what is likely to happen if the supply fails. I shall now attempt a qualitative answer to these questions in the light of current knowledge.

Coal, oil and natural gas are wasting sources of energy, and in due course will cease to exist. It has been estimated that, in this island already, we have raised 25 000 million tons of coal and that the readily accessible coal remaining is about twice that amount. On this basis and at a modest increase in consumption we shall exhaust the accessible coal in about 200 years. The total coal reserve is probably very much greater, but much of it would be extremely costly to win.

It is not easy to estimate the total coal reserves of the world, and although attempts to do so have been made, the results are subject to many qualifications—the thickness of the seam, the quality of the coal, its depth below the surface and many other things have to be evaluated before its economic worth can be assessed. Economic worth is a relative term which depends on the availability and cost of alternative fuels. Liquid fuel enjoys a somewhat special relationship to all others.

A recent American assessment of the world reserves of all fuels is shown in Table 1. This estimate suggests that the world reserves of crude oil are only about 5% of world coal reserves, whilst, with 1 : 1 breeder reactors, the potential energy of nuclear fuel is more than twenty times as great as that of the world reserves of coal, oil and natural gas put together.

Table 1*

Fuel	World reserves	Source of data	Total energy B.Th.U.
			$\times 10^{18}$
Crude oil	610×10^9 barrels	Weeks and Moulten	3·5
Natural gasoline	$11{\cdot}5 \times 10^9$ barrels	American Petroleum Institute	0·07
Shale oil	620×10^9 barrels	Bureau of Mines	4
Natural gas	560×10^{12} ft^3	American Gas Association	0·6
Coal	$3\,482 \times 10^9$ tons	Bureau of Mines	72·2
Total conventional fuel			80
Uranium ..	25×10^6 tons	Raw Materials Division of A.E.C.	1 700 at 1 : 1 breeding
Thorium ..	1×10^6 tons	do.	71
Total new fuel (say)			1 800

* Reproduced from Cisler, W. L.: "Economic Evaluation of the Industrial Use of Atomic Energy" (American Power Conference, March 1953).

The world annual consumption of coal is about 1 600 million tons and the consumption of crude oil is about 640 million tons. Unfortunately, simple arithmetic is of little practical value in computing the probable life of respective fuels in particular countries. There are some undeveloped countries with considerable coal resources in which the present use is negligible. On the other hand, highly developed countries are consuming coal at a rate disproportionate to their reserves. Furthermore, not all the known reserves are recoverable, although, on the other hand, more may be discovered.

With regard to oil, it has been estimated that consumption in the United States will be doubled between 1950 and 1975, and if this rate of increase were general the life of world reserves would be very much reduced. In view of the widespread tendency to use oil more extensively in agriculture and for sea, air and road transport, the supply of this fuel may easily become critical within the lifetime of the present rising generation.

This all too brief survey lends colour to the thought that, of the fossil fuels, oil will be the first to go. The efforts to produce a substitute liquid fuel may include the synthesis of coal, which, in turn, would accelerate the rate of destruction of this fuel. Even so, the reserves of coal are sufficient to allow time for the orderly development of alternatives. The geographical disappearance of fossil fuels will depend on the rate of uplift in relation to the amount of local reserves, and the rate of development of alternative fuels will depend, in the first instance, on their cost in comparison with that of local or imported fossil fuel. Obviously, the country with large reserves of all kinds of fuel is most favourably situated to maintain and expand its mechanized civilization, and provided it uses these resources economically and makes commensurate advances in its political and cultural life, it is probably destined to remain a world force for a longer period than other less well-endowed peoples. The importance, therefore, of the economical use of native fuel stretches far beyond the desirability of maintaining one's standard of living, although it includes it.

What then are the alternatives to fossil fuels? The general answer is nuclear fuel. I think, however, it would be wrong to give the impression that, although nuclear energy is there for the taking, it is a simple matter to release it in quantities suited to our requirements. Hitherto heat has been obtained by amputating and re-grafting the limbs of matter; in nuclear fission, it is proposed to tear out and divide its heart.

It is not possible to make an accurate forecast of what the future fuel situation will be. There are so many imponderables: the frontier of knowledge is being constantly expanded, Nature herself may take a hand as in the previous Ice Ages, and the reaction of humans to changing circumstances must be given due weight.

The increase in world population is an important factor. Ever since man's emergence from the Dark Ages, world population has been increasing. Curiously enough, this has been noticeable even in countries where technology showed no advance. Perhaps the general trend has been made possible through better means of communication whereby the effects of industrial technology and medical science are felt beyond the confines of the countries that initiate them. Whatever the reason, most countries have participated in the production of a world population which has enjoyed a four-fold increase during the last 300 years and is now growing by 20 millions a year—that is by more than 2000 an hour.

The fate of previous civilizations has been sealed when population outstripped the ability of their technology to provide sustenance and shelter, and the fate of our own cannot be dissociated from this self-same influence.

In this welter of possibilities, it may be of value to look at two possible alternative situations—one on the assumption that nuclear fission or nuclear fusion will not prove to be a practical means of providing power, and the other that it will.

Without atomic energy, the main alternatives to coal, oil and natural gas are water power, tidal power and wind power, with solar energy and geothermic heat available in certain zones, and wood, peat, and animal wastes each making its own contribution.

Water Power

The conditions which make water power most readily available are adequate rainfall on a large elevated catchment area, a suitable reservoir in which to impound water at this high level, a relatively steep conduit to a low level where the power unit is situated, and adequate means for disposing of the spent water.

Hitherto the assessment of world inland water-power resources has included only those which show prospect of economic development and are not required for other purposes such as navigation, irrigation or domestic use. In future, much more may be pressed into service, perhaps for dual purposes of which power will be one. However, the most recent estimates show that the world total of inland water power, 40% of which is in Africa, could supply at least three-quarters of man's present energy requirements.

One of the largest and most spectacular sources of water power lies at the western end of the Mediterranean. This inland sea loses water through evaporation which is not wholly recovered from its river inflow, with the result that water is constantly flowing through the Straits of Gibraltar, and to a lesser extent through the Dardanelles. If, therefore, both straits were dammed, the level of the Mediterranean would gradually fall, and having established a suitable differential it could be maintained by admitting water from the Atlantic through suitable turbines. Rough calculation shows that, with a differential of 70 ft, the inflow could develop 12 million kW, which is 75% of the present demand for electricity in Great Britain. It would require a modern Hercules to undo the work of his illustrious namesake, and no doubt the political repercussions would be considerable. The project is mentioned here only to illustrate the kind of thing that may have to be done in a more civilized world of the future when coal has ceased to be.

Tidal Power

Tides are produced by the combined gravitational effect on the rth of the moon and the sun. Since the liquid portion of the rth's surface is free to move, large oceans respond to the fferential attractive force at the nether and the further shore. inds and currents also play a significant part. The result is at, at any given point on the coastline of a large ocean, the lal lift normally varies cyclically twice in the course of a lunar ıy, twice in the lunar month and twice a year. The amplitude tidal lift varies from place to place. Since tides follow the oon and man's efforts follow the sun, the tidal cycle is not -ordinated to human needs, and, in this sense, tides are an ısatisfactory source of energy.

The simplest device for using tidal energy is to trap water in an tuary, or reservoir, at the time of high tide, and after the tide ıs receded sufficiently allow the trapped water to escape through rbines in which most of the energy due to the differential head converted into useful work. The daily work periods are cyclic, ıd their incidence in time of day also traverses twelve hours ıring each lunar month. There are devices, such as pumped orage and double-basin working, by means of which the energy ailable for external work can be controlled and better fitted human requirements. There is also a difference of up to two ours in the time of high tide at different places round our coast. a powerful electrical transmission system were available to onnect together all such points, it would be possible to take lvantage of these time differences to reduce the amount of ımped storage. So long as the harnessed tidal energy formed small proportion of the total energy in the electricity system which it was connected, it could be accepted as and when it was ailable without storage. The largest single tidal scheme in is country is that known as the Severn Barrage, and much ought has been devoted to the most effective way of harnessing e energy in this estuary. A number of comparable schemes e being investigated in other countries, but no tidal-energy oject has yet reached the construction stage.

Energy of the Wind

Force is required to move air from one place to another, the rresponding energy being proportional to the cube of the locity. It is practicable to abstract some of this energy by owing down the speed of air movement.

Because of the low density of the medium, the energy release r unit volume for speed changes likely to be achieved in any acticable windmill is quite small. Stated conversely, a windmill ust be a bulky structure with large-diameter vanes for even the latively small output of 100 kW contemplated in recent designs. urthermore, the wind bloweth where [and when] it listeth. It ould seem that, although there is a large amount of energy of ovement in atmospheric air treated globally, practical considera-ons will limit the contribution to be made by this source to a nall proportion of man's present-day energy requirements. owever, even this contribution may be welcome when coal and l have disappeared.

Solar Energy

The amount of solar energy reaching the land areas of the rth's surface is equivalent to 10 000 times man's present quirements, and this may be the source from which the final ientific civilization will obtain its energy. Unfortunately, owing the moderate temperature, the low intensity and the daily and asonal variations, there is little hope of producing mechanical ower by present known methods in any but tropical and semi-opical regions. Interesting developments are taking place in mestic space-heating and in solar cooking. Some 6 000 solar okers are being sold in India per annum, each capable of cooking a vegetable meal in about twenty minutes. If this practice extends, hundreds of millions of people will be able to cook their daily meal all the year round without using animal wastes for fuel. Soil fertility should improve correspondingly.

Neglecting, therefore, for the moment the possibilities of nuclear fission, the most reliable and economical alternative to coal and oil is water power if one looks at the world as a whole. However, the locations of possible water-power projects are such that quite fantastic power transmission schemes would be required to transport the energy to present centres of population. Apart from the political implications of such energy transfers across national frontiers, they present technical problems of a scale and type quite beyond anything that has been solved hitherto.

An alternative to transmitting the energy to the people is to transport the people to the energy source, and a considerable shift in the weights of population may well take place in the future if nuclear fission proves to be intractable as a source of industrial power. Great efforts would, no doubt, be made to ease the situation by developing tidal, wind and solar power in localities where there was little water power.

The foregoing assessment of the situation which may arise in the absence of a successful outcome of the attempts to harness the fission or fusion process for industrial purposes suggests that, when coal and oil are exhausted, it should be possible to muster man's present-day energy requirements from all the known sources, but that energy transmission or population transportation would present enormous technical and social problems. It underlines the absolute necessity to master the fission or fusion technique if the present pattern of civilization is to endure.

Nuclear Energy

Let us now look briefly at the nuclear-power possibilities.

Professor Einstein postulated that matter could be converted into energy. He calculated that the annihilation of one pound of matter would release energy equal to 11 340 million kWh of electricity. Were such complete conversion possible, six pounds of matter would release energy equivalent to the whole of the electricity generated in Britain last year. No means has yet been found to achieve this result.

It has been possible, however, to release a tiny fraction of the mass energy of matter by persuading a heavy atom to divide into two lighter atoms whose combined mass is a little less than that of the heavy one. Similarly, it has been possible to release energy by persuading a number of light atoms to form a single atom whose weight is a little less than the sum of the weights of the lighter atoms which combine to make it.

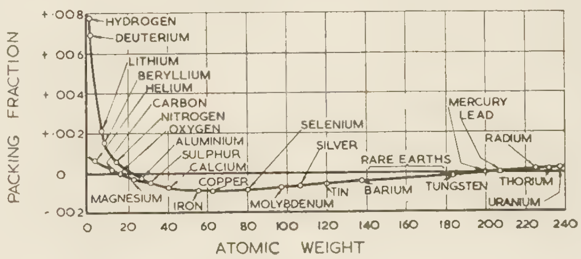

Fig. 1

Reproduced from KENDALL, J. T.: "The Production of Atomic Energy," *Engineering*, 1946, **161**, p. 75.

Fig. 1 illustrates some of the possibilities. In it are shown the deviations from whole numbers of the atomic masses of a number of elements on a scale in which the mass of oxygen is taken as 16. Some of these deviations are positive and some

negative. Theoretically there should be a release of energy when atoms with a more positive mass deviation divide or combine to produce atoms of a less positive or of a negative mass deviation. The division of uranium into two lighter elements or the fusion of hydrogen into helium offers the possibility of energy release. The diagram suggests that there are other possibilities.

Since hydrogen constitutes a substantial proportion of the earth's crust, the potential energy from the hydrogen-helium fusion process could be enormous. A practical difficulty is the sustained temperature at which this reaction takes place, and it would seem that, until something is discovered which will enable the reaction to proceed at a lower sustained temperature, the industrial application of this great energy source will remain unsolved.

From published data on the fission of uranium, it would seem that the process can be controlled in such a way as to liberate heat at a temperature suitable for industrial power purposes, but that before efficient large-scale nuclear power stations are practicable, work has to be done on heat-transfer methods and materials and on the treatment of the products other than heat which form part of the process. There can be little doubt that these problems will be solved if the need to do so is sufficiently great.

Of the uranium existing in nature, only about 0·7% is fissile. However, a process has been devised through which the remaining 99·3% can, by a double reaction, be converted into plutonium, which is fissile. Thus it is now theoretically possible to release in a controlled manner the energy of fission of all the uranium and perhaps the thorium content of the earth's crust. The practical and economic problem is to find the uranium and to separate and purify it.

From this point of view, it is unfortunate that uranium is so widely dispersed amongst the other materials of the crust. For example, it has been stated that the uranium content of a ton of granite, if it could be isolated, would produce as much heat as a ton of coal. However, there is no known economical method of isolating the uranium content of granite, and this is equally true for trace contents in many other common substances.

There remains, therefore, the problem of recovering pure uranium and thorium from their ores where they appear in forms and quantities that render the process economically practicable. It has been estimated that the availability and accessibility of uranium is such that (at present costs) an expenditure of £50 per pound of pure metal should be sufficient to mine and refine enough of this fuel to provide man's present energy requirements for 1 500 years. Similarly, on the same basis, an expenditure on less productive ores of up to £100 per pound of pure metal should procure sufficient uranium to last another 8 500 years. These very general figures should be taken only to indicate the satisfactory manner in which uranium can meet world energy requirements and, broadly, what effort would be required to render it available.

It is outside the scope of this Address to forecast the international problems that may arise from the geographical distribution of fissile material in nature, but without wishing to minimize them it can be said that they will just have to be solved if all peoples are to enjoy the benefits of a mechanized civilization.

There are some who argue that, because it is now theoretically possible for nuclear fission to satisfy man's total demand for energy, the pursuit of all other sources should be abandoned. I do not share that view. There are problems to be solved before the energy of fission becomes a reality on a large scale. The chemical process of uranium separation and purification will itself consume a considerable amount of energy, and in any event the alternative sources will be fully competitive for many years to come.

As coal and oil approach exhaustion, a possible balance may be found by harnessing all the water power of the world and, as far as possible, meeting local power requirements from this source. Where there is a local surplus of water power, the energy could be used to purify fissile material so as to provide power in lands where the alternatives are insufficient. Since fissile material, even in its natural state, is easily transportable, such packaged fuel might solve the power transmission problem.

Water power, tidal and wind power will, no doubt, be developed in many lands to minimize the need for imported fuel and the world production of industrial alcohol will probably be greatly increased to provide much-needed liquid fuel. Indeed one of the problems of the Atomic Age will be the provision of small mobile power units, and it may be that part of the answer will be found in the use of nuclear energy via a fuel cell. As far as can be seen at present, nuclear energy will be made available to the people as electricity. Electric rail and road transport will assume a new importance. Britain will become a smokeless zone.

In sum, therefore, man having evolved during a million years has, over the past 250 years, developed a mode of living which is unique in human history. This achievement has thus lasted for only 0·025% of his sojourn here and already it has made great demand on the energy resources of our planet. Unless he is able and willing to match his technology to the unfolding needs of the situation, he has no prescriptive right to a continuance of this latest civilization, and the history of civilizations discloses that discontinuity—decay and rebirth—is the normal method by which successive stages have been reached.

However, to-day man is equipped with a knowledge of natural laws (science) and an ability to harness these laws to his needs (engineering) that were absent in all previous civilizations, and there is good reason for thinking that the present mode of living can be greatly prolonged if he will but use this knowledge and ability aright. The test is one of competence in the political sense to learn how to live together in peace, and in the technical sense to unravel the unsolved relationships in nature and constrain them to serve his ends. The political aspect, though extremely important, and something for which all must share the responsibility, is outside our immediate scope this evening. But the progress of science and technology is the main object for which this Institution exists and, as events are shaping, is one of the two vital matters that will condition the future of the human race.

These twin challenges must be met if civilization is to endure and members of this Institution are in the front line on one of the battlefields. It is an exciting situation. The need for more and better physicists, chemists and engineers was never more clamant, the results of achievement were never more worth while and it is extremely important that in our homes and schools the need and the prospect should be fully explained to the rising generation on whose shoulders the responsibility for continuity lies.

We stand before the portals of an epoch. It is the privilege of scientists to unlock one of the doors through which humanity may pass to the enjoyment of a fuller and a freer life for the next 5 000 years.

Let us all see to it that man is worthy of his achievements.

Acknowledgments

This Address contains matter derived from general reading but the author wishes to acknowledge having read and drawn upon the following recent publications:

Ayres and Scarlott: "Energy Sources—The Wealth of the World" (McGraw-Hill Book Co., 1952).

Palmer Putnam: "Energy in the Future" (Macmillan and Co.)

Report of the U.S. President's Materials Policy Commission.

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Feb. 1955

UTILIZATION SECTION: CHAIRMAN'S ADDRESS

By J. I. BERNARD, B.Sc.Tech., Member.

"EDUCATING THE PUBLIC"

(ABSTRACT *of Address delivered* 21*st October*, 1954.)

In selecting a topic for an address it is not unusual to deal with ɔme subject with which one is personally concerned, but in ɛnturing to address you on the importance of educating the ıblic in the utilization of electricity, I am prompted by words ken from a Presidential Address to The Institution by one of s most distinguished members. The extract from that Address hich I wish to take as the text for mine is as follows:

> Not the lightest of the duties of the modern electrical engineer is that of *educating the public* in the use of electrical energy.

These words were spoken by R. E. Crompton 60 years ago. ı those days the only load on the generating stations was for ghting, and Col. Crompton went on to point out the importance ' developing the motor load and electric cooking and heating.

That was some time ago, and since then the annual consumpɔn of electricity has risen to 1 070 kWh per capita and the load ctor on the public supply system has increased to 45%. lectricity is no longer regarded as a mysterious force, and the dustry is well organized with an active Development Associaɔn and over 1 000 Electricity Service Centres engaged in lvising the public, to say nothing of all the other electrical ıowrooms and shops up and down the country; so the question ay be asked, Is not that enough? The answers I would give— ' way of justification of what is to follow—are, first, that the mark "it's electric," so often made to explain any modern achine or apparatus, indicates the acceptance of electricity as wonderful thing rather than any understanding of how it ɔrks. Secondly, although this is not the place to deal with ethods of advertising and publicity which are necessary to fluence public opinion in general, members of The Institution ould have, in my submission, as an article of faith in their lling, a readiness to educate, to inform or at least to give a tip to speak to fellow-members of the community, especially dustrialists, architects and others in important positions, as to ɔw electricity should be used or might be used in the interest of emselves and the prosperity of our country.

All too often, I suggest, electrical engineers are so absorbed their own problems that they do not stop to think how much lp the solutions might be to other people. In other words, I lieve we engineers, especially members of the Utilization ction, should not content ourselves with designing or making me new type of automatic control-gear or new piece of heating uipment, but should go on to explain to those who might use ch equipment exactly what it will do for them. We are the tter able to do this by having had in this Section a number of pers[1]—and it is hoped more will be forthcoming—dealing th the utilization of electricity in particular industries.

Industrial Productivity

The connection between the use of electricity in the factory d industrial productivity was clearly indicated by C. T. elling in his Address as Chairman of this Section in 1949–50, d since then a good deal of attention has been devoted to the greater amount of power available to the American operative than to the corresponding worker in this country.

It is generally agreed that the American operative has between $2\frac{1}{2}$ and 3 times as much horse-power at his disposal, but such a bald comparison cannot be used by itself as an argument that factory managements should install more or larger motors. The comparison is one of effects, and unless the causes are studied we shall be merely exhorting and not educating the industrialist. The reasons for the difference are in fact many and various; for example, American manufactured goods generally are much more standardized than those in this country, so that there is more scope for mass production and this means larger machines, often running faster, which require more power.

American machinery, particularly machine tools, is built to do heavier work; for instance, Woollard,[2] one of the leading authorities in this country, has pointed out that ". . . it has been a common failing for British machines to be under-powered. In America they tend to the other extreme and equip their machines with unusually powerful motors. If it is a fault, it is a good fault."

Another reason why figures of horse-power per worker are higher in the United States is that they have developed to a greater extent than we have in this country the automatic operation of process machinery, so that each worker operates, or to be more accurate, supervises, several processes. This development in production engineering is exemplified in automobile manufacture, for instance, by automatic transfer machines, as they are called, which replace a number of conventional drilling, boring or milling machines, on all of which in turn the workpiece had to be set up by hand by a number of individual operatives. In the transfer machine the workpiece is automatically clamped in position on each machining station in turn and transferred from one to the next automatically so that a cylinder block, for example, is milled, bored and drilled with all necessary holes, a total of perhaps 40 or 50 operations, under the supervision of only two or three operatives whose work may be further simplified by a series of signal lamps denoting correct or incorrect operation of each section, and in some cases automatic timing devices to indicate when tools should be replaced.

Analysis of production methods, particularly in the United States, where statistics are more in vogue than they are in this country, has established two general relations: one, the horsepower installed indicates the *method* of production, and two, the units of electricity indicate the *quantity* of production. It would I think be helpful in educating works managers and production engineers if those of us in this Section who are able to do so could compare figures of this kind in one factory with those of another in the same industry as an indication of the extent to which modern methods of mechanization have been adopted. In America they have interested themselves in yet another criterion, which is worth mention as it gives perhaps a clearer picture of how much electricity is being used to speed up production, and that is the units per man-hour. In the United States this figure rose from about $4\frac{1}{2}$ kWh in 1939 to nearly 7 in

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1950, and the aim of American electrical engineers is to raise it to 10 by 1960. The present figure in this country is no more than 2 kWh per man-hour.

One of the factors that is only just beginning to receive adequate attention in the quest for higher productivity is the subject of materials handling. Here, as in other spheres, electricity is directly concerned by providing the power for many kinds of equipment such as electric trucks of all types, conveyors, runways, hoists, and so on. Some of these have been developed by firms in the electrical industry, but the majority are supplied by specialist manufacturers of mechanical-handling equipment who make plant of all kinds, ranging from an electric pulley block to an elaborate overhead conveyor system like that installed at the Austin Motor Co.'s assembly plant, where car bodies, engines and sub-assemblies of some 800 different combinations are selected for automatic delivery to the assembly line according to a controller which receives punched cards compiled on the basis of sales requisitions or forecasts.

One type of mechanical-handling plant deserving special mention is the battery electric truck, which is now made in this country in a wide variety of designs and up to large capacities, including all patterns of the versatile fork-lift truck. It is a matter for regret that all mechanical transport used inside factories has not the cleanliness and silence of the electric truck, which has been proved to be less expensive to run than the internal-combustion-engined alternative.

Although mechanical-handling equipment and appliances take very little horse-power, they may have an important effect on productivity by cutting down handling time and so allowing a greater proportion of the operatives' time to be spent on productive work. Another important advantage of better materials handling is that it cuts out the "coolie labour" kind of work on which British workmen should not be engaged in the second half of the 20th century. It stands to reason that a man will do more work and will take more pride in it if he has an electric truck to drive than if he has to push a barrow or hand trolley. Detailed information on industrial uses of electricity is given in the E.D.A. Electricity and Productivity series of handbooks.[3]

Industrial Electric Heating

From its original application to small muffles for heat treatment in the laboratory, the use of electricity for industrial heating has now spread to practically all trades, particularly for processes requiring a clean, convenient form of heat, without any waste heat, which can be quickly applied and precisely controlled.

The most extensive use of electric heating is made by the metal-producing industries. Over 90% of all the high-grade brass is melted electrically, and in the steel industry arc furnaces have been particularly useful in recent years for melting and refining the large quantities of scrap that have had to be used, while most of the special steels for tool-making and similar purposes have been made in high-frequency induction furnaces. In the United States the arc furnace is beginning to be used for the production of plain carbon steel, and a recent report[4] claims that this tendency is sound both financially and from a fuel-saving point of view. The capital outlay for an electric furnace-shop with a capacity of 250 000 tons per annum is there estimated to be little more than half that required for an open-hearth furnace-shop, and the net production costs show an advantage to the electric furnace-shop of no less than 7 dollars a ton.

Many vivid illustrations of the various ways in which industrial electric heating can contribute to prosperity were given in the last Faraday Lecture by O. W. Humphreys. Electricity offers a wider range of methods of heating than any form of fuel because it is a form of energy which can readily be transformed into heat by an arc, by contact resistance, by induction or by dielectric loss in addition to the ordinary method of passing the curre through a resistance element. In particular, the use of hig frequency induction and v.h.f. dielectric heating has provid some notable, one might almost say revolutionary, aids to high industrial productivity. In the metal-working industries, harde ing or other heat treatment can be applied by a small inducti heating set which can be placed in the line of production a by means of automatic timing devices operated by unskill labour. Broadly, one can say that whenever some local heati has to be furnished for any purpose, heat treatment, brazi or soldering, it can be done more quickly and more precisely induction heating than by any other method.

For non-metallic materials there is the alternative of heating capacitance currents. The most elegant application of th principle is when advantage can be taken of the different dielectr losses of different materials to heat, say, synthetic glue used making plywood and to avoid heating the wood which form the bulk of the charge. The saving of energy and time striking; for example, an edge-gluing press fitted with radi frequency heating for making blockboard will turn out pane measuring 46 in × 16½ in with seven glue lines three times as fa as the method formerly used.

There are many industrial electronic applications especially the field of automatic control. Possible uses are so varied th one needs a clue as to which may prove worth while, bearing mind the cost of specially designed equipment. Broadly, it seem that the electrical method should be considered whenever the are measurements or inspections to be made which require mo than the unaided eye or which have to be made on large numbe of identical articles. As Sir Ben Lockspeiser[5] put it in a rece lecture, "Machinery has already removed the sheer drudgery toil over large areas of the world, and with the aid of electron machines—or the 'electronic brain' as it has been called—we a in sight of being able to remove the boredom of repetitive routi work."

Storage Heating

Turning to commercial buildings, the most common use electricity other than for lighting is for space heating, particular in the smaller shops, offices and similar buildings where th simplicity of the electrical method and the fact that it needs n labour or attention make it an obvious choice. Shortage an increased costs of solid fuel have also favoured electricity, but- it should be noted now—in many towns electric heating wa formerly sold to commercial users at tariffs which were belo the cost of supply.

As tariffs are made more realistic by introducing demar charges, the cost of electricity for heating during the daytime considerably increased, and so the public need to be educate as to the advantages of thermal-storage methods, which enab current to be taken at night and perhaps during the midd valley in the load curve, without incurring demand charges. view of the importance to the supply undertaking of balanci the night with the day load, the development of thermal stora is highly desirable. The idea, of course, is not new; it w advocated by Dr. Ferranti when he was the President of T Institution over 40 years ago. More recently the need for "a effective and economical system of heat storage" was emphasiz by Philip Sporn[6] in connection with his view that eventually a homes will be electrically heated.

There are now two new ways in which electric thermal stora can be applied; one, suitable for new buildings, is by means floor heating, which was first brought to the notice of T Institution by R. Grierson.[7] It makes use of the thermal capaci of a solid concrete floor by means of heating wires which consi of bare galvanized-iron wire supplied through a transformer

w voltage, or heating cables drawn into buried conduits, mineral-insulated metal-sheathed cables embedded in the ncrete.

The other type of thermal-storage heater now available is the orage block heater. This consists of an assembly of concrete similar blocks in a suitable containing case and heated during e night by an internal element. By careful design the heat ansmission paths through the storage block and the emission om the outer casing can be made to release the stored heat uring the daytime at a sufficiently constant rate, allowing for e fact that a warm office or shop first thing in the morning cilitates the start of the day's work, while during the afternoon isual heat gains from a rising outdoor temperature and other urces compensate for a somewhat reduced heat output from e storage block.

Commercial Catering

Now that the need for load shedding is passing, it is to be oped that the advantages of electricity for catering purposes ill again be brought to the attention of possible industrial and mmercial users. In addition to their other advantages, electric ookers of all types will help owners to comply with existing nd impending legislation regarding clean food preparation. erhaps a more decisive influence towards the choice of the best ethod of cooking, however, is the tendency to adopt self-rvice in canteens, cafeteria and restaurants which brings the istomer much closer to the kitchen. In the United States, here the degree of employment is not as full as in this country, ectric cooking equipment is now being installed in factory and her canteens as an added inducement to workpeople thinking f joining the staff and with a view to reducing labour turnover.

There is one other class of commercial establishment which ectricity can probably help to bring up to date better than any her single agency, and that is the hotel. Every visitor to a otel may legitimately expect to find public rooms and bedrooms ith a degree of convenience and comfort not less than he or e has at home, and yet how often does this occur? In fact would be reasonable to expect a hotel to have a superior andard of facilities. If only the proprietor were better educated his electrical adviser or, failing that, by some of his electrical sitors, we might see an end to badly placed bedroom lights, convenient switches, chilly grates and kitchen fumes in the ning-room.

Domestic Uses

The "all-electric" home has been talked about for so many ears that many people must have wondered whether it would er come true. The public supply of electricity had to be stricted for heating purposes until recently on account of ant shortages which were the legacy of a hard-won war, but -day, with the building of new power stations well under way, e are practically assured of an unrestricted supply at a price hich compares most favourably with other services or com-odities. In the meantime, in the years since the war, manu-cture of all kinds of domestic appliances has made rapid ogress in this country. The stage then is set for a continuation the expansion in the domestic use of electricity which has ken place in the last ten years.

The manufacture of electric cooking and heating appliances s always occupied a leading position, and there has not been ite so much scope for post-war development as in other pliances, the manufacture of which on a large scale in this untry is, comparatively speaking, an innovation. It may be ted, however, that the British-style cooker with grill boiler d warming cupboard under the hob continues to hold its own home and Commonwealth markets. Upkeep costs have been reduced by the E.D.A. Interchangeability Specification for replacement parts. When fitted with the latest refinements, i.e. quick-boiling radiant hotplates with continuously-variable control switches and a time switch, so that it will cook a meal by itself, our latest electric cookers offer all the facilities of American ranges, at a lower price.

For domestic hot-water supply the needs of the small household have been excellently met by the two-in-one self-contained electric water-heater, which in its nominal 20 gal size with heaters of 0·5 and 2·5 kW, as made by a number of manufacturers, keeps the full supply hot continuously; or, for those users who like to switch electricity off, keeps about 5 gal hot, sufficient for every need except baths and laundry. It is a gross injustice that such an economical heater, the ideal form of hot-water supply for all the flats that are being built in London and elsewhere, should be penalized commercially by a misconceived imposition of purchase tax.

The alternative of an immersion heater, although also subject to tax, is often preferred on account of lower first cost, and there is no technical objection to it, provided that the layout of the piping will not result in continual circulation of electrically heated water and so loss of heat, for example through a towel rail. Detailed guidance on installation problems is readily available.[8] When the immersion heater is installed, as it usually is, in conjunction with a solid-fuel-fired appliance, the power station gains some load in summer and loses some in winter, especially if the solid-fuel-fired appliance is of the continuous-burning type; and the user has to pay more for his hot water, especially if he has been unwise enough to avoid the cost of proper lagging of the hot-water tank. This practice of omitting lagging when using a high-grade form of energy as the source of heat is all too prevalent and inevitably enforces a hand-switching regime which is the antithesis of the convenience of automatic water-heating by electricity.

Motor-Operated Appliances

Hot water turns one's thoughts to the washing of clothes, which has become a regular chore in very many households.

The domestic type of automatic washing-machine is most popular in large households which are no longer able to afford commercial laundry prices. The machine, consisting essentially of a drum holding the clothes which is turned slowly for washing and rinsing and then fast for spin-drying, depends for its success on an automatic timing controller which allows the housewife to do something else while the machine does the work. So much mechanism having been provided, it seems a pity that the design has not yet been further developed in this country by adding a third stage in which the clothes are finish-dried by blowing hot air into the drum while it slowly revolves.

Other types of electric washing-machine have increased in number and variety of design. In some models, in order to simplify manufacture, the power drive for the wringer has been omitted, and although a number of users regret this omission a substantial proportion do not seem to object. On the other hand, the absence of facilities for boiling has been found to constitute a serious objection in the minds of many women, and so a heating element is offered by a number of makers as an optional extra fitting. It appears desirable, however, for such heating elements to have a rating of 3 kW or more in order to meet the demand for quick boiling.

As an engineering achievement the production in this country of refrigerators with hermetically sealed systems probably takes first place. Not only are these units likely to run without trouble for a longer time than the open-type compressors formerly used, but they also have an appreciably higher efficiency. The running cost of a domestic refrigerator is therefore negligible,

and useful additional facilities can be provided such as adequate storage space at about 0° F for quick-frozen food. In addition, freezer chests for seasonal storage of surplus food on the farm or private estate have become a practical proposition.

Domestic Heating

As regards the heating of domestic premises, an increased range of fires and low-temperature heaters of various kinds, convectors, liquid-filled radiators and radiant panels, are available, and there is a greater awareness of the value of thermostats for the control of any form of electric heating other than the personal warming provided by electric fires. For heating houses larger than those for which a single solid-fuel fire is sufficient, the most popular arrangement for winter use (electricity being exclusively used in spring and autumn) appears to be either some form of continuous-burning solid-fuel-fired appliance and electric heating elsewhere or else some background heating by electricity with an open coal fire in the living-room.

As shown by D. H. Parry,[9] better structural insulation would enable all-electric heating to be employed at no extra cost, but it is difficult to persuade architects or builders to adopt any unconventional method of construction, and as long as bricks and mortar can be laid relatively cheaply in comparison with timber or more highly manufactured materials, there is not much likelihood of houses being built which do not lose heat rapidly in all directions. Engineers will naturally lose no opportunity of advocating better thermal insulation, and in the meantime the use of electricity for partial or auxiliary heating is bound to increase. One advantage of the wide choice of heaters available is that electric heating can be "tailor made" to cope with the cold corners, draughts and other thermal idiosyncracies of English domestic architecture.

Turning to other household uses of electricity, the range of British-made labour-saving appliances has been notably increased by new types of kitchen mixer which can be fitted with so many different attachments that they will perform practically every food-preparation task and will add quite materially to the cook's ability to produce attractive soufflés and other dishes; they should certainly be made known to all who are keen on cooking.

New and improved types of vacuum cleaner, floor polisher, hair-dryer and sewing-machine are also available, and from an engineering point of view it is interesting to note that shaded-pole motors are tending to replace the commutator type. The reason is not any pronounced reduction in the number of houses supplied with direct current, but is probably due to the need for radio interference suppression, increased by the introduction of television. Where the commutator motor must still be used on account of its higher speed, mainly in vacuum cleaners, radio interference suppression has been simplified by the introduction of double-insulated construction which permits larger capacitors to be connected to the motor frame without increased risk of shock.

Adequate Socket-Outlets

The convenient use of portable appliances depends to a great extent upon the provision of an adequate number of socket-outlets fixed in suitable positions. There is no doubt that a uniform size of socket with fused plug, i.e. the flat-pin 13 amp type to B.S. 1363, as introduced after the war to facilitate ring-circuit wiring, is by far the most convenient type of outlet, since with an appropriate fuse in the plug, any type of apparatus can be safely connected. Members of The Institution should, it seems to me, lose no opportunity of extolling the convenience of the "universal" socket-outlet, as I think it should be called. It can, of course, be used for rewiring apart from new installations, and with ordinary as well as ring circuits.

The lack of socket-outlets in most houses is always an inconvenience and must in time act as a bottleneck on electrical development. It is easy to blame those engaged on installation work, whereas it might be more correct to say that the whole of the electrical industry has not made its weight felt in shaping public opinion. An adequate number of sockets should always be regarded as part of the essential equipment of a house for convenient living.

Safety of Appliances

Electrical engineers can also use their authority when necessary to reassure those members of the public who still tend to regard electrical appliances as containing an element of danger.

At the end of the last war the possibility of unsafe apparatus coming on the market was foreseen, and an influential committee, the Advisory Committee on Electrical Appliances and Accessories, was formed jointly by the E.D.A. and the B.S.I. to deal with the matter. The Committee's policy is to invite anyone to send in particulars of any unsatisfactory apparatus. If the Committee, basing its judgment on a report by the E.D.A. Testing House, decides that the complaint is justified, the manufacturer is advised privately. The result of the Committee's work during the last seven years has been to rid the market of unsafe apparatus, and manufacturers who are in any doubt about the safety of new designs of appliances are now accustomed to submit them to the Committee while they are still in prototype form and alterations can be easily made.

In addition, the Committee has instigated the production of additional British Standards for domestic appliances, including electric fires, vacuum cleaners, irons, kettles and heating pads, while others are in course of preparation. As part of its work, the Committee also keeps in touch with domestic apparatus design in other countries through its membership of the C.E.E. (International Commission on Rules for the Approval of Electrical Equipment).

Finally it may be said that the most perfect appliances may not be proof against careless handling or deliberate misuse, and the public should be warned to use them properly, to switch off when not in use and not to attempt repairs that they are not qualified to do.

It is, I believe, in such ways as those described that the electrical education of the public can be greatly helped by all members of the Utilization Section.

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SUPPLY SECTION: CHAIRMAN'S ADDRESS

By J. D. PEATTIE, B.Sc., Member.

"1910–1954"

(ABSTRACT *of Address delivered 27th October*, 1954.)

The maintenance of the traditions of The Institution is a task id on all members. Its importance is very much in the mind f a Section Chairman when giving his Address in the Lecture heatre, surrounded by portraits of the founders of our profession. t times, they seem eager to pass a message to the generations ollowing them. Of this select band, Dr. Ferranti, as President, elivered his Inaugural Address* 44 years ago in the present ecture Theatre. It was an amazing exposition, well worth ading at the present time. Ferranti was one of those choice pirits touched by the prophetic fire. He spoke in 1910, four ears before the First World War, three years before the peak ear, 1913, of coal production in this country, and at a time hen public electricity supply was using about 3½ million tons f coal per annum. To-day we have two world wars behind us nd are in the throes of the so-called cold war. In this country oal production is only about 78% of the 1913 figure and public ectricity supply absorbs more than 10 times the amount of oal it required in 1910.

Ferranti's theme was a threefold one—coal conservation, ome-grown food, and better utilization of our labour. We ight now, with advantage, compare Ferranti's vision with resent-day realities, assess briefly where we now stand, and erhaps look forward a little into the future. But before we scuss details, I would like for a few minutes to examine the osition of supply engineers in the scheme of things.

We are told by scientists and some philosophers that the single omponent of the material universe is energy. In its active form exists in various forms ranging from the very highest grade, tensely concentrated in mass, to the lowest grade in heat waves oursing throughout the universe. In our part of space-time ere is an inevitable steady one-way non-reversible flow from the ghest intense forms to the lowest form. We have given ex- ession to this fact in the second law of thermodynamics.

A tiny fraction of this flow of energy from the store in the drogen atoms of the sun washes over our planet in its journey t into space. Our material existence is, in fact, a participation the conversion process. Primitive man, like lower forms of e, depended for his existence on the flow of light and heat ming directly from the sun. When he discovered how to start d maintain fire, he began raiding the stores of energy, caught d stored for a few months or years in timber. He accelerated e conversion process and in so doing began to raise what we e pleased to call his standard of life, and to gain more leisure r pursuits other than hunting. He has been busy with this deavour ever since. He used these stores to provide light and at. For power he depended in the first place on his own modest rformance as a heat engine, but later he used domestic animals, ling water and wind to drive his primitive machines.

The discovery of coal unlocked the doors to much greater and ore easily used stores laid down some 200 million years ago, d, once again, the conversion process was accelerated. A little er he discovered how to channel the conversion process through heat engines to give him mechanical energy. Still later, a little over a hundred years ago, he forged a new link in the chain of conversion, by turning the mechanical energy into electrical energy, capable of transmission and application with unexampled ease and precision. It is at this point that supply engineers begin to find their place in the scheme of things.

Quite recently, man has once again unlocked the doors to still older and vaster stores of energy, probably laid up, we are told, 3 000–5 000 million years ago in the nuclei of atoms. He is beginning to accelerate the conversion of these stores, and once again we, as electrical engineers, are in the first line of those who carry out and control these accelerated conversion processes for the benefit of our fellows.

Having plotted our position in present-day society, let us turn back to Ferranti's vision of 1910. He dealt in the first place with coal conservation—a problem of the first importance at the present time. Listen for a minute to his summary:

> It appears that, with a problem such as we are discussing, it is fundamental that the energy in the coal should be converted at as few centres as possible into a form in which it is most generally applicable to all purposes without exception, and in which it is most easily applied to all our wants and is at the same time in a form in which it is most difficult to waste or use improperly.

Having stated the problem, the solution was clear. Ferranti continued:

> We are therefore forced to the conclusion that the only complete and final solution of the question is to be obtained by the conversion of the whole of the coal which we use for heat and power into electricity, and the recovery of its by-products at a comparatively small number of great electricity producing stations. All our wants in the way of light, power, heat and chemical action would then be met by a supply of electricity distributed all over the country.

To those of us who spend our lives living with the innumerable petty irritating problems of everyday engineering, it is refreshing to read those quiet words of faith coming from one of our great predecessors. The vision of 1910 is, when we think seriously, the obvious fact of 1954. The 20th century is one in which man is gradually coming to accept Ferranti's conclusion. The future may hold alternative solutions, but, for the present, electricity is supreme as the most useful link in the chain of conversion from the store in the fuel to use by man and final rejection as low-grade heat.

So much for the broad vision, but Ferranti did not content himself with generalities—he gave certain estimated figures to support his views. It is not to be expected that the estimates would be accurate in detail, but it is stimulating to retrace a part of the 1910 arguments and compare them with present-day facts.

Ferranti took as a basis for his calculations the requirements being satisfied in 1903 by a home consumption of 150 million tons of fuel, excluding 2 million tons going to coasting steamers and 15 million tons then used by gas works. He proposed to take 60 million tons of coal only, convert it into 131 400 million kWh of electricity and use it to supply the whole of these varied requirements.

Let us pause here for a moment and consider the conditions

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under which this estimate was made. At that time, published figures for certain electricity supply works showed a consumption by them of only 1% of the total coal burnt in Great Britain. Information since collected indicates a consumption for statutory generation in 1903 of about 3 million tons—still less than 2% of the total.

We have at times need of some of that boldness of conception of our future. Instead of timid estimates of the next few years' progress on conventional lines, we would do well to take heart and consider possibilities, not merely certainties. By all means let us take the immediate next step deliberately, but let us also take it with our eyes on the distant objective. Supply engineers have too often grossly underestimated their share in supplying the long-term requirements of the nation.

But the total requirements themselves are continually rising. Since 1903, the population of Great Britain has risen from 37 829 000 to 49 286 000, and the demand for energy in one form or another by each individual has also risen.

Great strides have been made in the efficient use of coal in many directions, particularly as Ferranti foresaw, by conversion to electricity, and we have travelled far from the 1903 position. Curiously enough, there has been comparatively little change in the total home consumption of fuel, which reached a peak value in 1913 of 200 million tons, fell to 160 million tons between 1930 and 1934, and has once again risen to 206 million tons in 1953. At the same time, consumption for statutory generating stations has risen from 3 million tons in 1903 to 37·2 million tons for the 12 months ended 30th June, 1954. From that 37·2 million tons we sent out from our stations 63 000 million kWh of electricity.

We have indeed travelled some little distance along the path and the prospect is changing, but the future is perhaps more exciting than ever. Let us examine a little more closely the main categories of use to which electrical energy is put.

So far as the controlled production of light is concerned, electricity is supreme, and the continual improvement in the conversion of electrical into light energy is merely consolidating that supremacy. But as quickly as the efficiency is being improved, society is increasing its demands for light, and the drain on the primary stores of energy for that purpose grows.

In the case of heating, the story is far from complete, and controversy still rages about the best chain of conversion processes to satisfy our needs. Too often, attention is concentrated on a single stage in the process and improper use is made of the ease and accuracy with which electrical processes can be measured. I disagree strongly with many loose statements which are made about waste in these electrical processes. For that matter, all energy is ultimately wasted. At the end of the conversion process, when man loses interest in it, all energy goes its inevitable way in the form of low-grade heat. During all processes there are inevitable leakages and only a minute fraction is usefully employed. Nature herself is lavish. Only a tiny trickle of the flood pouring from the sun washes over our planet and, of that trickle, only a minute fraction affects our lives.

When we turn some of that fraction into electricity, we immediately bring it under close control for use in the required amount precisely where we want it. To repeat Ferranti's words, we have it in a form in which it is most generally applicable for all purposes, without exception, and in which it is most easily applied to all our wants, and is at the same time in a form in which it is most difficult to waste or use improperly.

Man's use of the energy stored in fuel for cooking and heating is very ancient, but the cooking and heating efficiency of the cave fire certainly left plenty of scope for improvement. If we take as our aim the controlled provision of heat for individual use and comfort, and assess dispassionately the various methods available at the present time, then electricity is certainly the intermediate form which can be most easily applied and us properly with least waste for both heating and cooking. F various reasons, we have resigned ourselves to forgoing its u for long-period space heating, but even that conclusion m have to be revised sooner than many imagine. The increasi difficulties in providing the special fuels required for small a medium heating installations and of controlling individual u of large district-heating installations give opportunities f electrical space heating.

In industry, electricity for process heating has still a wide fie for development. As our efficiency of generation from low-gra fuels rises, our use of nuclear fuels begins to become significa and the choice of special fuels becomes restricted, the conditio will change in favour of electricity for process heating.

There is one large-scale application of electricity for heati purposes, mentioned in 1910, which even now in this country m seem fantastic. I do, however, commend it to your attentio Ferranti suggested that iron ore should be smelted electrical using coke only for the chemical reduction process. Now v are all well aware of the wonderful progress which has been ma in the use of coal for producing iron and steel. The iron an steel industry shares with the electrical industry the credit f remarkable progress in technique and efficiency. But our ri as an iron and steel producing nation has been bound up with t use of the magnificent British hard coking coals. These are with sight of exhaustion, and the remaining reserves are becomi more and more difficult to extract. In the steel industry, nati coal is being replaced by imported oil. Ferranti's suggestion beginning to look much more attractive than it did in 191 With the increasing production of electrical energy by nucle power stations, conditions will again change. From the iron an steel industry itself, signs are not lacking of a search for radical new processes in manufacture and treatment. It is our oppo tunity to offer help in the controlled supply of heat through t medium of electricity on a scale far beyond present practic leaving coal or coke to be used in the chemical reduction proces

Turning now to the supply of power, the dream has certain come true and the whole world is conscious of the effect on man productivity of the use of electrically driven machinery. Tea after team of the earnest seekers after the secrets of America achievements have emphasized the importance of an eve increasing supply of electrical energy in the factory, on the lan and in our homes. At present, one half of the total output electrical energy from our stations is used for power purpose and still we are far behind our friends in the United States.

I cannot refrain from referring once again to what has so oft been said in this theatre about railway electrification. I sha the recent heartfelt sigh of *The Times* leader writer:

> There may be some reason why Great Britain, with its shorta of large coal (which is now being imported) and the smoke-lad air of its cities and its rising transport costs, may still be the o country in which the old form of steam locomotion remains t most economic. But it is unlikely.

An excellent example of British under-statement.

The direct use of electricity for chemical processes, particular for the production of light metals and alloys, has been multipli many times by the demands of two world wars, and we are on on the fringe of new developments in that respect. The nam of metals which were curiosities in 1910 are now almost househo words, and their numbers increase every year.

I will not attempt to analyse in detail the changes which ha occurred in the supply of artificial fertilizers and the reasons f the lack of interest in Ferranti's proposal to process the co using the gas for firing electrical power plant and produci ammonium sulphate and other valuable by-products. I woul however, remind you of the change which has taken place in t

quality of coal mined and, still more, in the quality available for electricity generation.

There is now a sharp distinction between carbonization and industrial coal. Reserves of carbonization coal are approaching exhaustion; industrial coal is steadily decreasing in quality. At the same time, the proportion of large coal is falling and that of small coal is rising rapidly. Furthermore, the ash content of that small coal is steadily increasing.

Many influences are forcing us to use larger and larger units of boiler plant for which pulverized raw coal is the most attractive fuel. The economic balance at the moment favours, therefore, the direct use of the relatively high-ash-content small coal in pulverized form for firing these large boiler units. Despite costly attempts, it has not been possible to develop the idea of processing coal to produce gas for combustion at generating stations and by-products for sale to the artificial-fertilizer and other markets. Ferranti did suggest the fixation of atmospheric nitrogen by the use of off-peak electricity, but development of fertilizer production has taken somewhat different lines, and the threatened shortages of the early years of this century have, in fact, been averted by a combination of processes.

Before we glance at the future, may I summarize the main features of our present development?

Coal in this country is in short supply. So far, the hopes of the immediate post-war period have not been realized. During and after the war we have made great inroads in the seams available for opencast working and used such coal largely at generating stations.

We now seem committed indefinitely to the import of coal or other foreign fuels. We are burning oil in quantity at one station —Bankside—and shall in the near future be burning oil at another major station—Marchwood, on Southampton Water. We are considering plans for provision of dual-firing oil or coal at a number of other stations. We are just beginning to experiment seriously with the use of nuclear fuels. The problem of fuel conservation has indeed, for the nation, become acute. But as electrical engineers we can face the grim prospect with some confidence. We have adjusted ourselves to meet the changing conditions. The country is now nearly covered with a network of transmission and distribution lines connecting the great generating centres with each other and with the ultimate consumers. So far we have been able to increase the capacity of individual lines by steady increase in voltage up to the latest circuits now in use and under construction at 275kV. It is in the nature of this network that it can, with great ease, be extended and increased in capacity to meet consumers' requirements. We are therefore ready to convey the electricity to the consumers according to their demands, efficiently and economically. Our colleagues in the Utilization Section are facing their problems in the same spirit.

At the generating centres we are beginning to gain control once more after the tremendous strain of war and immediate post-war conditions. Despite the difficulties of construction, we have added some 6 million kW of output capacity since 1948, and our annual rate of increase is round $1\frac{1}{2}$ million kW, rising, we hope, by 1960, to nearly 2 million kW. This estimate is not at all excessive and allows no margin whatever for unforeseen increase in demand by consumers.

At the 30th June, 1954, the B.E.A. had in its 281 stations an installed capacity of 19 million kW. We are approaching Ferranti's 1910 figure of 25 million kW in 100 stations.

After stagnation during the war, efficiency of generation has once more begun to rise normally. The average of 23·54% for the 12 months ended 30th June, 1954, is also within sight of Ferranti's lower limit of 25%. We shall certainly pass that within a year or two.

Individual stations are recording annual sent-out efficiencies up to 31%. One always rejoices in the performance of the star member of a team and welcomes its stimulating effect on other members, but the team supporters are also interested in the average performance. Since the 1st April, 1948, 123 units have gone into commission in new stations or new sections of existing stations. Table 1 gives a general picture of the recent performance

Table 1

THERMAL EFFICIENCIES FOR 12 MONTHS ENDING AUGUST 1954

Group pressure (stop valve)	No. of sets (At end of period)	Total installed capacity (At end of period)	Thermal efficiency (sent-out basis)	Efficiency ratio
lb/in²		MW	%	%
1 200–1 500	5	300	30·5	61·5
900	52	2 956·5	28·1	60·4
600	64	2 328	26·1	59·8
400	2	40	23·6	58·3
	123	5 624·5	27·38	60·3

of four main categories of this plant grouped according to steam pressure. In comparing these figures with more spectacular figures for individual units, it should be remembered that they are on a sent-out basis, that they are average figures for groups of units, and that they cover 12 months' normal operation to suit system requirements.

Intimately connected with the problem of efficiency is the size of generating units. Up to the present the steam turbo-alternator has held the field and has been successfully developed to meet the changing conditions. It is often convenient to take as a rough measure the doubling of demand in each decade. In Britain, turbine design has followed a similar pattern, distorted to some extent by the war years.

The effect on our programmes of the rapid evolution of larger units can be seen in Table 2, which summarizes the plant actually commissioned in 1952 and the plant we expect to commission in 1959.

Table 2

SIZES OF TURBO-GENERATORS

Installed capacity of individual sets	Commissioned in 1952		Programmed for 1959	
	No. of sets	Total installed capacity	No. of sets	Total installed capacity
MW		MW		MW
20			1	20
30	13	395		
40-50	11	540		
60	9	540	11	660
75	1	75		
100			4	400
120			5	600
200			1	200
Total ..	34	1 550	22	1 880
Average size, MW		45·6		85·5

Table 3 shows the corresponding data for boilers. The conventional k.lb/h unit of capacity is used. The better unit of B.Th.U. per hour would be more appropriate, but this is less familiar. As electrical engineers, we should welcome the use of the megawatt rating, which is already being used for nuclear plant.

Table 3

SIZE OF BOILERS

Installed capacity of individual boilers	Commissioned in 1952		Programmed for 1959	
	No. of boilers	Total capacity	No. of boilers	Total installed capacity
k.lb/h		k.lb/h		k.lb/h
100	13	2 240		
200	9	2 050	1	200
300	35	11 665	2	600
400	2	850		
550	2	1 100	9	4 950
755			2	1 510
830			2	1 660
860			5	4 300
1 400			1	1 400
Total . .	61	17 905	22	14 620
Average size k.lb/hr		294		665

While it is well to keep always in mind the grand objective of ever-increasing use of electricity, we cannot avoid concern with the difficulties in achieving our end. Some of the more important arise from the relations between the supply industry and the community. The two problems associated with the use of rivers and estuaries for the supply of cooling water and those arising from the discharge of flue gases and dust are at present much in evidence.

An adequate supply of cooling water is essential for the efficient and economical operation of a thermal station. The stage is now being reached where the natural flows of British rivers are inadequate for our purposes. River Boards, under their new powers, are placing severe restrictions on the permissible temperature rises at power stations, and increasing use has to be made of cooling towers, the make-up of which is, in many cases, the effluent from sewage works. But cooling towers evaporate practically the same amount of water as was condensed in the condensers. This is a significant quantity at large stations. In addition, cooling tower ponds have to be purged at regular intervals, thereby returning to the rivers all the solids and dissolved salts in the incoming make-up. As a result, new sites using rivers are becoming increasingly difficult to find, and great care has to be taken in the futuie planning to meet the River Board requirements. Suitable coastal sites are more scarce than might be imagined from a brief glance at the map.

An allied problem is that of atmospheric pollution from power station chimneys, an important part of the larger problem now being studied by the Beaver Committee. There are two distinct aspects of this—the emission of solid particles and the emission of certain gases such as sulphur dioxide.

With the increasing use of pulverized fuel, rapid strides have been made in the efficiency of electrostatic precipitators, which, in this country, hold the field for extraction of the fine dust from the flue gases. Much work is in progress on the problem. Recent measurements at Little Barford, a station in flat, open country, have shown that the small residue of dust leaving the chimneys does not settle within two miles of the power station in quantities which can be measured with certainty by the standard dust gauges.

So far as sulphur compounds are concerned, the costly experiments on flue-gas washing at Battersea, Fulham and Tir John generating stations lead to the conclusion that the best solution of the problem is to discharge the hot unwashed gas from high chimneys into the upper layers of air, well clear of buildings, where they are dispersed innocuously over wide areas. The proposed use of oil, with its higher sulphur content, as an alternative fuel, adds to the difficulties. Gas washing has been enforced at Bankside, where the boilers are oil fired. It is debatable whether better results would not have been obtained without flue-gas washing. Nuclear-fuel-fired stations will certainly have allied problems in the disposal of radioactive residues. These difficulties will be overcome as they arise and their nature becomes better known.

This short review of the 1910 prophecy may have refreshed our minds. Too often, supply engineers have underestimated future demands for electricity.

In Great Britain, electricity consumption has doubled on the average every 8 or 9 years since 1920. Suggestions that that process will continue for several decades are met by two lines of argument, namely that saturation will be reached sooner rather than later, and that we are now a poor country which cannot afford that kind of progress. So far as saturation is concerned, we need only glance at other countries, such as the United States and Canada, with consumptions per head of the population far in excess of ours, where demands for electricity are still rising steadily without sign of saturation. The other argument hardly explains the same steady rise in demand of countries with far less resources than our own. The truth is that we cannot afford not to progress electrically.

Fig. 1 shows, on a logarithmetic scale, the rise in the consumption of electricity per head of population since 1920 in a

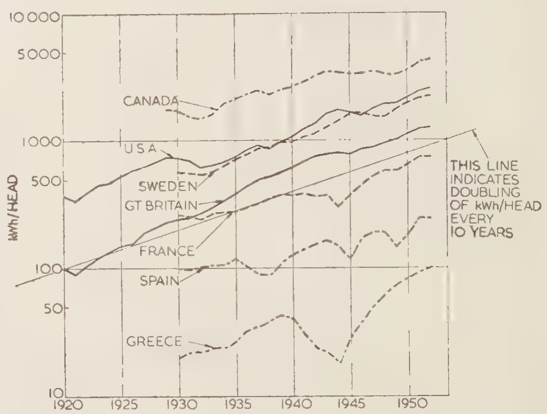


Fig. 1.—Output of electricity per head of population (public supply only).

number of countries ranging from Canada to Greece. I have inserted a straight line to show the slope corresponding to doubling every 10 years. There is no indication of saturation per head of population in any case.

As immediate deliberate steps, the B.E.A. plan to provide an output in 1965–66 from their generating stations of approximately 120 000 million kWh, compared with 62121 million kWh in 1953–54. But it would be quite wrong to regard the 1965–66 figure as a ceiling. On the contrary, until man relinquishes his struggle for a higher standard of life and for more leisure, or until some better link than electricity in the chain of energy conversion appears on the scene, we, in this Section, must always keep before us a bold vision like that outlined to The Institution in 1910.

I began by suggesting that our predecessors, whose portraits hang on the Theatre walls, had a message for us. It is, I think, the simple stirring old injunction: *Sursum corda*—Lift up your hearts.

Abstract No. 1817 M
Feb. 1955

MEASUREMENTS SECTION: CHAIRMAN'S ADDRESS

By M. WHITEHEAD, Member.

"ELECTRICITY METERS"

(ABSTRACT *of Address delivered* 19*th October*, 1954.)

It may be thought that "Electricity Meters" is a somewhat arrow subject on which to address the Measurements Section. ideed, viewed against the great variety of human interests, igineering itself may be considered somewhat narrow; electrical igineering, narrower still; and electrical measurements even ore so; whilst the electricity meter is but a small part of ectrical measurements.

How then can an engineer devote the whole of his efforts to ich a narrow interest? The answer lies in the fact that when e inquire a little deeper into the subject—in fact, into any ibject—we become involved in an increasing number of asso-ated subjects until not only is the whole sphere of engineering cluded, but the whole of human activity. It is thus only the id-product or the end-measurement which is narrow, whilst ie experience is wide. The subject can be one of absorbing terest.

Many young electrical engineering graduates avoid these irrow and older subjects. Many are carried away by the amour of newer devices and their applications, and by the esire to gain what is called a wide experience. But there may more danger in the search for the goal of wide experience an in the concentration of effort on a narrow objective, ecause the wide experience will necessarily be shallow, whereas e narrow objective thoroughly investigated always leads into ider fields.

My subject was the main concern of the Section in its early iys, and the following comments on theory, design, manu-cture and application are some of the matters that occupy e time of an engineer engaged in metering. The basic unit om which all present-day metering stems is the single-phase duction watthour meter, numbered in a great many millions roughout the world, on which depends very largely the com-ercial transactions between the supplier and the user of ectricity. Superficially it is the most simple of devices, but on ialysis the subject becomes extremely complex and highly athematical. However, a physical and descriptive treatment to some extent possible.

The most elementary conception requires us to provide a iving torque which is proportional to the power, and—in der that the speed of the rotor should in turn be proportional the power—a braking torque which is proportional to the eed.

Production of Motion

Starting from a point on which there is complete agreement, can say that a disc is set in motion when it is cut by two ernating magnetic fluxes which are displaced in space and in ne. Analysis then proceeds along two different paths. In e first, the two magnetic fields are considered to combine to oduce a resultant field which moves in space; the second ethod considers the two fields separately and supposes that otion is due to the interaction between one of the fluxes and e disc currents produced by the other.

Mr. Whitehead is with Ferranti Ltd.

The moving field may be obtained either by the vector summation of the instantaneous values of the individual fields, or it may be obtained by the resolution of the individual alternating fields into components rotating with equal but opposite angular velocities, the components being summated. It is sometimes referred to as a rotating field, its similarity to the induction motor being stressed. The wide disparity in the two constructions, however, has been emphasized by others, who would suggest that this theory is incorrect. In making this comparison it is often assumed that induction motor theory is free of conflict. This is far from the case, and consideration of unbalanced phase voltages usually raises a doubt. When the voltage of one phase of a 2-phase motor is progressively reduced the motor continues to furnish mechanical power and a point is reached where in addition it starts to feed electrical power into the low-voltage phase. When this circuit is opened the motor continues to function as a single-phase induction motor. It is at this point that the rotating-field theory is frequently discarded in favour of the "cross field" theory, which is the counterpart of the stationary-field theory in meters.

The controversy as to whether the moving field really exists still goes on and the debate continues as to which method should be used in teaching.

Whether or not we are able to visualize a moving field in either a single-phase motor or a meter, its application to a meter can account for the shapes of the current and voltage characteristics. Certainly, the separate stationary-field theory leads to easier treatment and understanding in the earlier stages of the analysis of performance. In consequence, there is a strong leaning to this method and most published analyses have used it.

Conduction Field

Whichever method of analysis we prefer, we are confronted with the calculation of the force and torque set up between an element of magnetic flux and an element of electric current, the latter being produced in two ways; first, by transformer action, and secondly, by relative motion of disc and flux. In effect, the problem is the determination of current in the disc; and over the last half century much ingenuity has been applied by many investigators in theoretical and experimental attempts to determine the distribution.

Theoretical investigations have varied from the very elementary with many assumptions to the most advanced using elegant and powerful expressions but demanding the discipline and constant practice of mathematics.

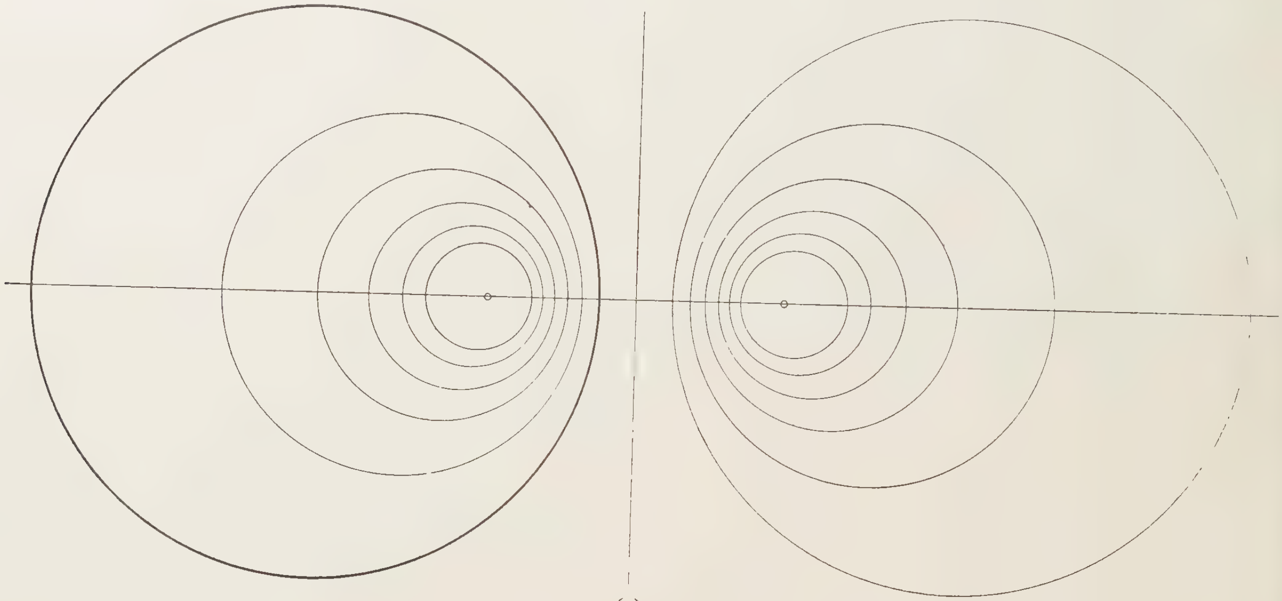
Some authors, in recent years, have said that long industrial experience has produced excellent performance, but they have also suggested that our knowledge of the theory and calculation is not good. They have then proceeded to expound methods which have been known for many many years. Independent confirmation is useful, but it also suggests that the methods are not sufficiently well known and perhaps justifies reiteration.

Before we can compute it is necessary to formulate, and one of the oldest methods is to adapt our problem so that we may

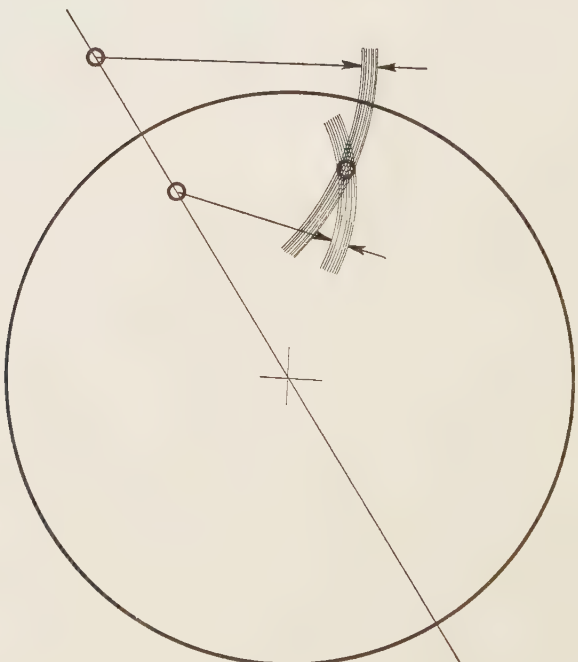
use well-known field patterns with known solutions which may be analysed and synthesized. These fields usually involve simple shapes such as straight lines and circles.

The boundary of our conductor (the disc) fulfils this requirement, but the magnetic flux boundaries do not. The magnetic flux density varies and does not disappear completely at any point on the disc. Non-uniformity of magnetic flux density may be overcome by subdivision and the consideration of each part separately. The problem is then amenable to descriptive treatment, and the computation, although laborious, involves simplest of mathematics.

We consider first a long thin filament conductor carry current and visualize the magnetic field in a plane at right an to the axis of the conductor. The flux lines are concentric circ The next stage is to consider two such thin conductors para to each other and carrying current in opposite directions. then have two series of concentric circles overlapping each oth and because the magnetic effects are linearly related to



(a)



(b)

Fig. 1

rents, the two fields may be superimposed and directly nmated to give the resultant field. The resultant field consists ircles enclosing each filament conductor which do not overlap h other and are no longer concentric with the conductor. s is a well-known field pattern in electrical engineering appears in every textbook on electricity and magnetism g. 1(*a*)].

f now the thin conductors are replaced by thin filaments of rnating flux cutting an infinite plane conductor, the induced rents follow precisely the same paths as the lines of force n the long conductors. Any one circle of current flow losing a filament of alternating flux may be taken as the ndary of a disc in a meter, and the distribution pattern is npletely unchanged by so doing. This is the well-known hod of images and inverse points.

n a meter, the magnetic flux is never in the form of a thin ment—it always has a finite area—and the next stage is to sider pole areas which are circular in shape. Just as one the eccentric circles enclosing a filament of alternating flux ld be taken as the boundary of the disc, so a smaller eccentric rent circle may be taken as the boundary of the pole, and in the current distribution in the disc is known in a com- atively elementary manner.

t is thus easy with simple shapes such as circles to determine distribution of the current. In an actual meter, however, e areas are not circles nor is the flux density constant, and in lition there is a leakage flux which extends beyond the area he pole face. This situation has been dealt with by dividing flux area into regions each of which is considered to be of istant flux density and which may in consequence be replaced a line of flux. Individual current distributions may be deter- ned and may be superimposed to obtain the total distribution. e object of this determination of current distribution is the culation of the driving torque, and here we are concerned h the interaction of the eddy currents already established h another alternating flux.

n computing the torque we may use either of two methods: first is to obtain the total current between two eccentric les, which involves finding the resistance of the circuit inded by two eccentric circles; in the second method the field ivided into component concentric circles and the torque due each is obtained, the resultant torque being the difference ween the two [Fig. 1(*b*)].

Currents set up as a result of the relative motion of the disc the magnetic flux may be dealt with by similar methods. We sider an area of magnetic flux through which the disc is ven, and in which e.m.f.'s will be set up in radial directions g. 2(*a*)]. The area is now divided into narrow strips by a es of arcs drawn from the centre of rotation [Fig. 2(*b*)]. se arcs are of constant potential and each strip may be con- ered to be analogous to a uniform electric double layer (layer electric dipoles or doublets). It may also be considered logous to a magnetic shell or to an equivalent magnetic shell g. 2(*c*)]. The interest of these analogies lies in the fact that forces may be considered to be concentrated at a point at end of the strip. The component field pattern at each end- nt consists of radial lines and concentric circles. The end nts may therefore be replaced by line currents or line charges y filaments of time-varying magnetic flux.

he current distribution in an infinite disc may therefore be rmined, and in consequence the force and torque. The dis- ution in a finite disc may be found by the method of images nentioned earlier.

number of assumptions are made:

) Magnetic fluxes are varying slowly (low-frequency alter- ng magnetic flux).

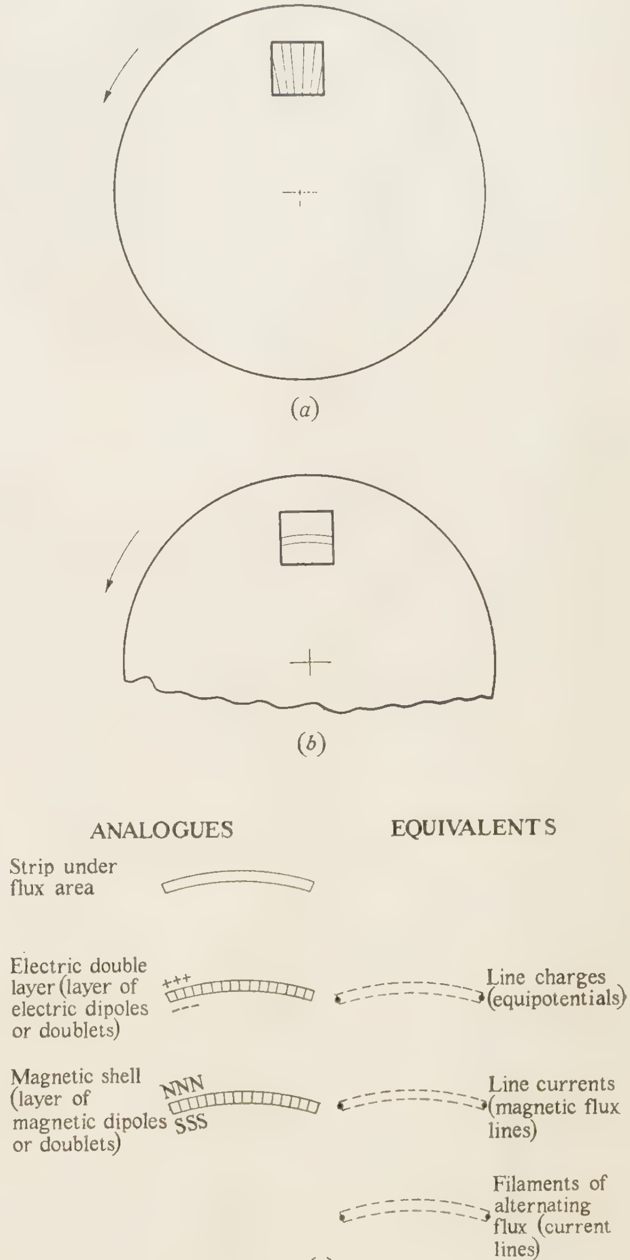


Fig. 2

(*b*) The fields due to the disc currents have negligible effect on main field (i.e. do not distort it).

(*c*) Effect of reactance of disc is small, and it does not affect superposition.

Turning to the measurement of the disc currents, most of the attempts have been applied to currents induced by transformer action rather than to motionally induced currents; i.e. to driving currents with stationary discs rather than to braking currents with moving discs. First amongst these should be mentioned the use of minute search coils, whereby the magnetic field is explored with and without a disc; in this way the magnetic field due to the disc currents can be determined and hence the currents themselves. Potentials set up by currents flowing in a mercury trough have been explored. Very minute current transformers

have been used, fitted through holes in the disc so that a small section of the disc forms the primary of the transformer. A further method uses a small area of constant magnetic flux, to explore the area of the disc, the amplitude of vibration of the disc, which is resiliently mounted, being measured.

A recent attempt to determine experimentally the distribution of motionally induced currents utilized two small brushes to trace lines of constant voltage. A null method was used, so that no current was taken from the disc. The lines of constant voltage

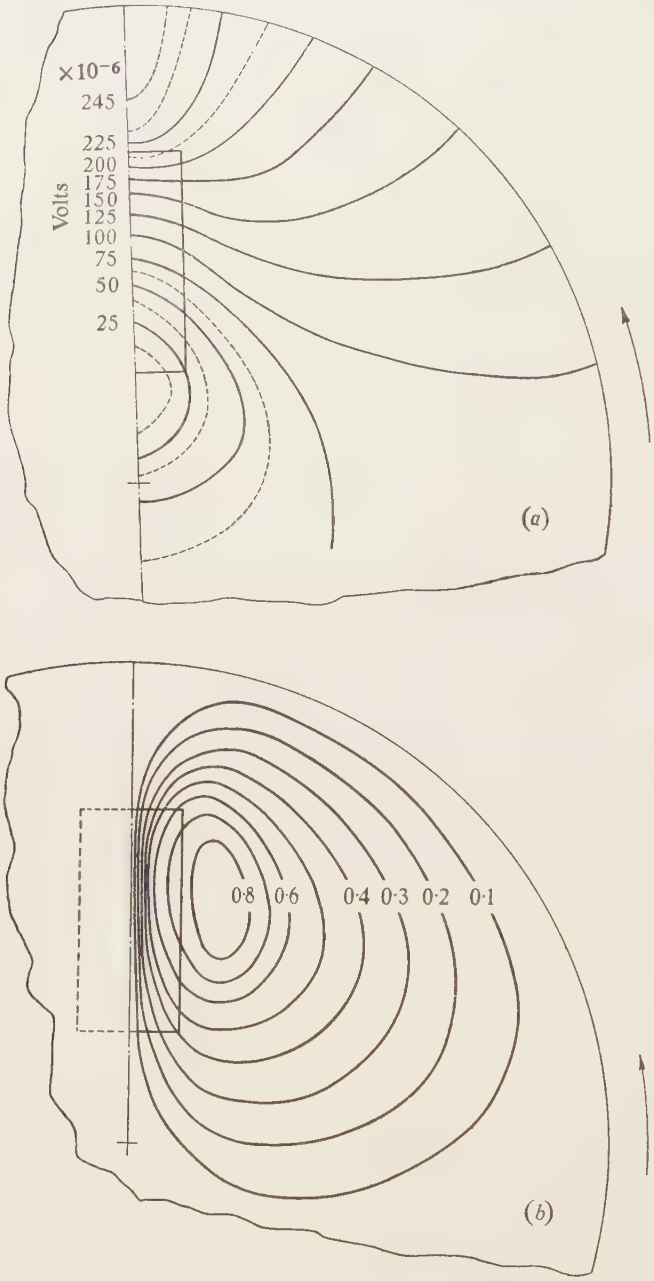


Fig. 3

are shown in Fig. 3(*a*); these must not be confused with the equipotentials of an electric field because they occur in a region of generation. They are really no-work lines. The next step was to calculate the radially induced e.m.f.'s. The measured and calculated figures were then converted to gradients, and from the two families of curves, the *IR* drop per unit volume an hence the current density. From the current density curve flow lines of current are obtained as shown in Fig. 3(*b*), where tl total current between adjacent lines is constant.

Error Curves

The discussion of the electric conduction field, and in cons quence the calculation of the driving and braking torques, lead naturally to the evaluation of the equation of motion and t the determination of errors. The non-linearity of the iro magnetization curves causes a departure from proportionalit between voltage and current and the respective fluxes, so tha the driving torque is not strictly proportional to the power.

The electromagnetic braking torques follow a relation t speed which at first is directly proportional, and with furthe increased speeds is less than directly proportional, until a maxi mum is reached when a decrease in braking follows a furthe increase in speed. This effect is due to disc eddy currents pro ducing a distortion of the main field. Over the speed rang normally used in meters, however, braking may be considere proportional to speed.

The electromagnetic braking may therefore be said to b proportional to the square of the flux and to the speed where, o the stationary field theory, the fluxes are those due respectivel to the voltage winding, the current winding and the permanen magnet. The flux of the permanent magnet, both in magnitud and distribution, should be independent of time and the suppl and load circuit variables, and the braking may be considered t be proportional to speed. The voltage flux, however, is approxi mately proportional to the voltage, and its braking to the produc of the voltage squared and speed. Since speed is directly relate to voltage, the braking is proportional to the cube of the voltage Similarly the current-flux braking is proportional to the cub of the current. These last two braking forces are responsibl for much of the error in voltage and current characteristics.

Measuring Range with Variable Current

A meter, of course, integrates power with respect to time an registers watt-hours. The largest variable is not the voltage o the power factor but the current. It is therefore the range o power with variable current which is probably the most importan characteristic of a meter. The ratio of maximum to minimum current over which acceptable and stable performance is obtaine is therefore important. It is easy to adjust a meter to give a apparently long range by careful adjustment at low loads, onl to find that the low-load error is variable. Long experience ha shown that a stable lowest load is associated with a driving torqu at this point of the order of 0·2 g-cm.

An illustration of the development of measuring range i shown in Table 1. It relates to meters which have been mad in large quantities and have a torque of not less than 0·2 g-cm a

Table 1

MEASURING RANGE OF ELECTRICITY METERS WITH CURRENT A SOLE VARIABLE

Year	Range (fraction nominal load)	Ratio max/min
1910	$\frac{1}{20}-1\frac{1}{2}$	30
1920	$\frac{1}{20}-1\frac{3}{4}$	35
1930	$\frac{1}{20}-\frac{3}{1}$	60
1940	$\frac{1}{20}-\frac{4}{1}$	80
1950	$\frac{1}{20}-\frac{5}{1}$	100

imum load, and the measuring range is that over which the or falls within a total band of 1%. The continuous extension r the years, with no trend towards finality, shows that meters not fully developed in this respect and that further improve- it may be expected. Advantages which accrue from the g range are that fewer ratings need be manufactured and ked, and the necessity of changing with growth of load is iated.

ın obvious, though not always appreciated, consequence of a g measuring range is that the rotor speed must have the same ge. The requirements of low current-flux braking and low hanical wear usually limit the speed at maximum load so the speed at minimum load has tended to be lower.

Economics

considerable effort is being continuously made to improve technical performance of electricity meters, and these rovements are ultimately passed on to the user. At any e in the development of the art, however, it is natural that performance should cost more than low performance. e electricity is the subject of a commercial transaction, the nomics must be sound, and two related questions naturally e: What level of technical performance should we use; and much money should it cost?

nmediately the subject of costs is raised it is almost invariably gested that a lot of money could be saved if supplies were metered at all. It may be that those who are directly engaged he industry have evaded this question, but it is better to face issue squarely.

he answer to the argument that the use of meters may be ded altogether lies in the combination of two features of an tricity supply which are absent from other supplies or ices, namely its energy content combined with its great bility and convenience of conversion. In the absence of a er there would be lavish and wasteful consumption chiefly hermal loads. Demand would go up and diversity down. e copper would be required in the distribution system, more sformers, more switchgear and generators. The simple l charge would have to be increased and increased until nately it would become prohibitive. Consumers would fall on other and inferior forms of energy because, under this f, electricity had become uncompetitive. The experiences electricity supplies in this country during the last decade happily behind us) provide sufficiently dramatic illustrations his possibility. During a discussion on this subject before Institution earlier this year, a majority supported the view the very existence of an electricity supply system depended 1 the use of meters.

further suggestion made repeatedly in recent years concedes use of electricity meters at present cost levels but states that e cost of electricity became very low, say one-twentieth of the ent figure, there would be no need to meter. This is difficult omprehend, because any form of energy of great con- bility would need to be measured and paid for individually. suggestions must have been based on the idea that the ern of life would remain unchanged with energy at one- tieth of the present cost. More likely would be a revolution e pattern of life.

ssuming that the cost is going to decrease it will presumably o gradually or in small steps as advances proceed. This have gradual repercussions on our mode of life, our con- ption of energy will slowly increase and the necessity of suring will remain.

here remain the related questions of performance and cost. ethod of approach already suggested is based on the argument that, with a system supplying a large number of consumers, the specified accuracy is required primarily in the interest of the consumer. The supply authority interest would be met by a lower accuracy because:

(*a*) The meter would still check the wasteful consumption which would occur without a meter.

(*b*) The meter would still meet the desire to distribute charges between consumers in a reasonably equitable manner.

(*c*) Concern is with the effective accuracy of groups, and the distribution of errors follows a Gaussian curve, the centre of which departs very little from zero error. High and low errors, then, largely compensate each other. This applies also when the figures are weighted to take account of consumption.

The consumer, on the other hand, with perhaps only one meter, is concerned that the positive error should not exceed a reasonable figure.

It is suggested that the economics should be decided on the basis that a consumer's payment should be a minimum assuming the meter to be set at the positive limit of error.

It is necessary to be clear as to what is meant by accuracy of metering, and to make an assessment of costs at different levels. The main function of a meter is to register the number of kilo-watt-hours over a period of time, and we are therefore concerned with the average error after it has been subject to the variables of voltage, frequency, current, power factor, temperature, etc. It is assumed that the error is that at which it has been left at some major point on its current characteristic.

An assessment of the annual costs of metering against various items is shown in Table 2, in which some figures (shillings) based

Table 2

e	0·5	1	2	4
Meter	10·5	6·75	4·35	3·0
Installation	1·2	1·2	1·2	1·2
Maintenance	3·3	2·7	1·95	1·5
Reading	3·0	3·0	3·0	3·0
Power loss	6·0	4·95	3·0	1·5
Total	24·0	18·6	13·5	10·2

These figures cannot be precise, but they nevertheless indicate trends.

on pre-war values have been increased by a factor of three. They assume a life of 20 years and the meter cost takes account of purchase price and retirement value.

If now the metering charge is isolated from the supply charge, the consumer's payment takes the form $P = U + M$, where U is the price of energy consumed, and M the metering cost. Owing to meter error, the supply charge is $U(1 \pm e/100)$ and payment as a percentage of supply charge is $100\,(1 + M/U) \pm e$. Taking $U = 600$s., the maximum percentage payments are 104·5, 104·1, 104·2 and 105·7 for accuracies of 0·5, 1, 2 and 4, respectively. There is a minimum between 1% and 2%, which represents the economic level.

The effect of a two-part tariff containing both a fixed charge and an energy charge is to move the minimum point in the direction of greater error. Thus there is an economic level of accuracy which is related to consumption and to fixed charge, and this suggests the use of different degrees of accuracy—for different classes of consumer.

An endeavour has been made to emphasize two very important aspects of electricity meters—the conduction field on the scientific side and economics on the commercial side. Their further study should result in better technical performance and in better application.

DISCUSSION ON
"ELECTRICAL DISCHARGES IN AIR-GAPS FACING SOLID INSULATION IN HIGH-VOLTAGE EQUIPMENT"*

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 2ND NOVEMBER, 1953

Dr. W. G. Thompson: The idea of a discharge without electrodes may appear strange, but examples of it occur on insulators under high-voltage stress and in some forms of discharge tubes.

The presence of bound charges on insulating surfaces is more familiar, although it also leads to some very interesting problems, particularly on the ultimate nature of the attachment of the charge to the surface.

It may be difficult to understand how small charged particles, such as electrons and ions, are able to produce discharges of the magnitude indicated, but it must be remembered that, although the charge of an electron is $4 \cdot 76 \times 10^{-10}$e.s.u., the voltage resulting from the accumulation of such a charge on the surface is given by the ratio of the quantity to the capacitance.

The importance of this work in connection with turbo-alternators and similar machines is obvious, and the development of the pattern shown in Fig. 3 from a single point to a radial arrangement of discharges is most striking. I am not certain whether this diagram is a result of a single pulse or a succession of half-pulses. The idea of a succession of half-pulses also interests me, because it correlates in many ways the two parts of the paper.

Another correlation is given in Fig. 7, since this does indicate the sort of pattern which we may expect to materialize within one of the voids referred to in the latter part of the paper.

With reference to dust particles, the authors have given some of the explanations in terms of polished and clean surfaces, but I imagine that, in applying this work to turbo-alternators or other machines, the picture they obtained showing the influence of the dust particles is more likely to occur in practice than the patterns associated with clean surfaces.

The recurrence of a discharge before the voltage zero is reached, when the applied voltage is actually falling, is also very interesting. Would the authors comment further on this point?

Mr. W. Renwick: Referring to Fig. 3(*c*), it would seem that the brightness of the secondary-discharge traces along the surface from the central main discharge is due to the many small discharges feeding into them. It is stated that a fundamental feature of the discharge with the positive electrode bare is that the positive pattern extends over a very large area. One would imagine that the time taken for the complete pattern of Fig. 3(*c*) to develop should be relatively large compared with that for a breakdown in a plane air-gap, i.e. both electrodes bare. Can the authors state the relative times?

Mr. A. R. Blandford: The various stages of air-gap breakdown illustrated in Figs. 3, 4, 6, 7 and 8 of the paper are identical with records first obtained from a klydonograph some 30 years ago. This is a simple instrument using the same operating characteristics as those described by the authors, and its low cost makes it suitable for use in relatively large numbers as a surge recorder. Unfortunately its accuracy of magnitude measurement is as low as 50%, and certain interpretations of its records of waveshape are questionable. This disadvantage considerably decreases its usefulness.

The authors consider that difficulties can arise with gas-filled gaps at voltages down to 1kV, and I suggest that this lim could be raised, with safety, to 3kV.

Referring to the method of bringing out stator conductc shown in Fig. 1, I suggest that the same result could readily achieved by earthing the outside of the insulation surroundi the conductors for a distance of a few inches from the ends of t core, which would prevent any discharge in air between t conductor insulation and the face of the core.

Mr. S. G. Crooks: Reference 12 of the paper deals with t breakdown of 33kV cables in a railway system with rectifi harmonics present. I wonder whether the authors could confir that the present theory would be a full and sufficient explanati for the breakdown of these cables, which I think was at the tin put down to an increase in the effective peak value of the volta wave owing to the harmonics.

Dr. E. Friedlander and **Mr. J. R. Reed** (*in reply*): In reply Dr. Thompson, Fig. 3 is a single half-wave discharge produc by the circuit shown in Fig. 2.

The recurrence of discharges before the voltage zero is reach would normally be expected. The remarkable feature of observed internal discharges is that these reverse discharg before voltage zero just do not occur as early as indicated fro elementary theory.

We agree with Mr. Renwick that the time taken for the di charge pattern of Fig. 3(*c*) should be relatively large, but it w still be a small fraction of an a.c. half-cycle. Precise times ha not been measured.

In reply to Mr. Blandford, the only reliable figure on whi one can generalize is that internal gap voltages must be in exce of 300 volts for discharges to take place. The relevant supp voltage which could lead to discharges therefore depends on t ratio of applied voltage to gap voltage, which differs with t type and perfection of the dielectric.

The well-known method of stress control by conducti surfaces in the overhang of alternators is not quite equivale to insulating the fingers of the pressure plate. The resistan of the conductive paint must be very carefully matched to t individual case. If the resistance is too high the paint is i effective in the vicinity of the slot edge, while if the resistance too low the critical stress point is only shifted to another ed further away from the stator core. Apart from the matching dif culty the long-term stability of resistance paint presents a proble

Mr. Crooks's assumption that the present theory would he to explain the breakdown of cables, dealt with in an earlier pap is quite correct. We hinted at the possibility at the time, b were not able to state, for certain, any effect of harmonics oth than the increased peak value. It may, however, be worth noti that the growing instability of "protective surface charges" wi increasing applied voltage, i.e. increasing charge density in a void, accounts for a very much greater liability of these surfa charges being lost in the vicinity of the peak value, and th therefore, small increases of the peak value in conjunction wi ripples at the top of the voltage wave are likely to increase t rate of destruction of a dielectric out of all proportion to t absolute increase of the wave peak. The real effect, therefo may well be a combination of both the "trough" and the "pea influence.

* Friedlander, E., and Reed, J. R.: Paper No. 1464 M, March, 1953 (see **100**, Part IIA, p. 121).

Abstract No. 1818
Feb. 1955

NORTH MIDLAND CENTRE: CHAIRMAN'S ADDRESS

By W. A. CROCKER, Member.

"MANAGEMENT AND MEN"

(ABSTRACT *of Address delivered at* LEEDS, *5th October*, 1954.)

n any industry, success is founded upon the relations existing ween management and employees. In the small workshop by the "boss" there will be an intimate knowledge of each his men—his excellence in one direction and limitations in other. The aims of the boss will be just as well known by his ployees, and such intimate knowledge and mutual undernding will lead to a sense of partnership and service which is beneficial in the production of good work. In a large and ttered undertaking such as a Sub-Area of one of the Electricity ards the same intimate knowledge is well-nigh impossible, l yet the same good relations must be maintained. The nager of a Sub-Area must closely interest himself in these ations by personal contact with as many as possible; neverthe- s the day-to-day contact will devolve on the district officers, whom as much authority should be delegated as possible.

This delegation of authority is of great importance, and it must practised at many levels. If responsibility is not delegated to district officers, employees will hardly know to whom they ould look in cases of difficulty. If work is not properly egated, those who should be giving their time and attention to portant matters will be cluttered with detail work, and matters ich could be effectively dealt with at a low level will be passed m one person to another and take up the time of all concerned, h resulting delay in action. But wasted time is not the only verse effect. If the Manager requires matters of minor portance to be referred to himself, a lack of initiative will be d in the staff at all levels. There sometimes arises a fear that responsibility is passed downward someone will make a stake. Of course someone will make a mistake some time, it is a fundamental and far graver mistake to curb initiative. sponsibility and the opportunity to exercise initiative will se an officer to give more careful consideration to every blem before arriving at his conclusion than if everything he s is subject to the decision of one or more above him.

The saying that everyone is in favour of delegation provided t it does not pass below himself is glib and quite untrue. e who is trusted will trust others, and one allowed initiative l allow initiative to others below him.

One of the most interesting aspects of management is the pointment of staff, any care taken being amply repaid over years of service expected. The salary of each man represents onsiderable expenditure by a Board, which can perhaps be ter appreciated as a capitalized sum. Very careful considera- n is given to the choice between two engineering schemes, and less care is necessary in the appointment of a person; other- e serious repercussions can result, not only in the particular for which he is appointed, but quite possibly throughout the ole undertaking. The interest in making appointments is anced by the necessity to assess fairly a candidate's personality. knowledge and experience are easily ascertained by direct stion and answer, but his personality is solely a matter of gment—after determining what he knows one must discover v he thinks, and his answers to questions should reflect, ording to the appointment, his ability to get on with staff and labour, his capacity for leadership, or his manner of dealing with consumers and the general public.

The immediate superior should have a predominant share in the short-listing and interviewing of candidates, and should be encouraged to state his choice, for it is he who will be most closely responsible. On the other hand, the final choice calls for a degree of moral support, and some guidance is often necessary. For example, one candidate may be better fitted from experience to give the immediate assistance which is always considered urgent, whereas another will commend himself as of greater future value, especially if he has qualifications which will equip him for future promotion. Need I say how essential it is to put each candidate at his ease and make the interview as intimate and informal as possible?

In the filling of staff appointments one has to weigh the relative advantages of two courses—the promotion of local staff and the bringing in of new blood. Promotion is a stimulus of great value to employees and thereby benefits the industry. If there is a general forward movement of personnel, every man with any ambition will strive to be in the current. Those who have endeavoured to equip themselves by study will see a chance of reward, and those who are in the course of training will be encouraged to continue.

The bringing in of new blood may discourage some in their long and arduous fight, especially if, by some accident of judgment, the outsider proves not so good as his application and interview indicated.

On the other hand, the continual promotion of men in one undertaking may result in a stagnation of ideas, acceptance of existing methods without question and an insularity which can become narrow-mindedness. It might be thought that the very size of each Board's Area would provide the solution, in that promotion within the Area would be sufficient encouragement to those in training and so give the necessary stimulus, at the same time obviating stagnation by a free movement from one part of the Area to another. I, personally, doubt whether such movement provides the desirable new blood in view of the growing standardization of practice within an Area.

The problem may be solved by local promotion in the lower-grade posts by advertisement within the Area and the advertising of high-grade vacancies in the national technical Press. My personal opinion is that the great majority of appointments should be advertised nationally in order to preserve the spirit of adventure. Great honour is due to the man who, in one undertaking, rises from the ranks to hold the highest position. Such a man is exceptional in his mental and personal endowments and would be successful whatever his opportunities or difficulties. For the others, there is a lot to be gained in moving from one place to another—at reasonable intervals, of course. They not only widen their experience but gain in confidence and broadness of outlook.

The Interest of Men in Management

There has been a good deal of discussion on the increased interest which should be taken by employees in management of

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the industry. What is the position to-day? First, I think, it can be said that management is spread over a greater proportion of the staff: the Sub-Area Manager is himself an employee carrying out the policies of the Chairman and Chief Officers of the Board. The Heads of the four Sub-Area Departments—Engineering, Commercial, Accountancy and Secretarial—are Managers of their Departments, and their Section Heads also take their share in management.

When we come to manual and clerical workers, participation in management is covered by the term "joint consultation," which, with the advent of nationalization, is being practised to an increased and possibly increasing extent, workers being continually urged to take a greater share. Their opportunity lies in the various levels of three national councils and associated committees—the National Joint Industrial Council for manual workers, the National Joint Council for clerical workers and the National Joint Advisory Council. There are District Councils of each at Area level, and Local Committees at Sub-Area level, the latter being known as Works Committees, Staff Committees and Local Advisory Committees, respectively.

The Local Works and Staff Committees deal with personal matters such as working hours, time recording, time and method of payment of wages, arrangements for holidays and the settlement of internal grievances.

The Local Advisory Committees are wider in their representation and scope, comprising technical, clerical and manual workers, working jointly as a combination. Their functions are to discuss and make recommendations on matters affecting the safety, health and welfare of employees, and on other matters of mutual interest including efficiency in the operation of the services of the Board.

Under the headings of health and welfare, the advisory machinery has undoubtedly effected considerable improvement during the past few years, for example in the provision of better washing facilities, adequate ventilation and the like, and consultative advice on occupational diseases and chronic affections. First-aid teams are now well organized, opportunities for social intercourse have been fostered and canteens have been provided where necessary. In the matter of safety, the general theme has been the prevention of accidents, the drawing-up of safety codes for work on high-voltage circuits, and provision of better facilities in the handling of materials. All accidents are discussed by the Local Committees, and there is no doubt from my own records that an appreciable reduction in accidents has resulted, not only from remedial measures, but also from the increased consciousness of risks and their avoidance.

One commendable outcome of the Joint Advisory Council is the suggestions scheme now operating throughout the industry, whereby suggestions from employees are considered carefully at District Council level in conjunction with the Area Board and rewarded according to merit. The awards have in the past seemed to me somewhat modest, but there appears to be a trend towards increased recognition of valuable suggestions. The interest of employees has been fostered by the scheme, and this, perhaps, is just as important as any resulting improvement in methods of operation.

It is under the heading "other matters of mutual interest including efficiency in the operation of the services of the Boards" that the most interesting problem arises as to the extent of participation in management by employees. Many such items have been brought to the Local Advisory Committees with some advantage and indicate a quickening interest in our service to the public. The committee members are certainly very interested in this side of joint consultation, and some of the general body of employees are mildly interested, but there are a great numb who evince not the slightest interest. I would venture to say th whilst the present contacts with management are appreciate very few would wish a greater part in management to be take

The three committees mentioned have, however, resulted in closer contact between management and employees than ev before, especially when one takes into account the larger un of the industry. Management, through these committees, has better appreciation of the personal and operational problems employees and their outlook, and, I am sure, the employ members have become more appreciative of the need for caref consideration of matters which concern the Board, the consume and the employees themselves. There is a better realization management's responsibilities in controlling an undertaking ar in controlling labour, and the committee approach disposes any feeling of management versus men.

The Joint Advisory Council have dealt with the subject education and training with enthusiasm, and it must be admitte that the whole of this field is now well organized. There a wide opportunities for the apprentice, engineering traine clerical staff and indeed all employees. There is also, I think, greater interest by management in the education and training each individual, for the industry is constantly in need of me fit for promotion.

The new education and training schemes are sometim criticized as making it so easy as to sap the individual endeavou of the young aspirant. There may be something in this view but the industry could not afford to leave it to a few individua to make their way; there would be too few qualified men, an their training would be much too narrow. I have, howeve noticed in some young engineers, who have had a college cours and undergone training, an inclination to rest on these qualifica tions and cease their endeavour to befit themselves for promotio but to expect that promotion will come by a series of automat steps. Such men need reminding that the higher posts ar reached by keen competition and their chance of attainmen depends on continued effort to acquire knowledge and experienc More than once have I seen promotion go to one without th advantages of a college course and intensive training but who ha kept his eyes and ears open and made every effort to learn wha was going on around him.

Education and training of an engineer are merely the prepara tion of the novice, and it is essential that on completion of th preparatory period he should gain experience on the reall practical side. The young engineer in our industry should be sen out to the district where the actual work of distribution is carrie out and not allowed to start in some planning job in an offic This would seem elementary, but I have interviewed so man applicants for engineering and commercial appointments wh have been made use of in an office instead of the field that consider it should be stressed—there is a moral obligation her on the part of management.

Summing up, I would say that one of the most importan functions of management is to maintain good relations throug out the whole of the staff. There should be wide and sensib delegation of authority with the object of encouraging th exercise of initiative. Management has become less an autocrac being shared by a greater number of senior staff with the co operation of employees in general through the medium of join consultation. Facilities for education and training are such tha opportunities exist for any aspirant to attain a high position.

Finally, management and men have been brought into close contact through the medium of joint consultation, with advantag to both and resulting benefit to the industry.

Abstract No. 1819
Feb. 1955

NORTH-WESTERN CENTRE: CHAIRMAN'S ADDRESS

By Professor E. BRADSHAW, M.B.E., M.Sc.Tech., Ph.D., Member.

"LABORATORY WORK IN ELECTRICAL ENGINEERING COURSES"

(ABSTRACT *of Address delivered in* MANCHESTER, *5th October*, 1954.)

This Address relates to laboratory work in general, but ecial attention is directed to the problems of the initial stages.

Aims and their Realization

Laboratory work should aim at:

Direct tuition in the standard methods of measuring electrical antities and the use of standard items of measuring equipment.
Understanding of topics treated theoretically in lectures and apprecia- n of the limitations of the idealized treatments which are of necessity d in much lecture work.
Familiarization with the appearance, construction and capabilities apparatus, and with the magnitudes of electrical quantities.
Cultivation of a critical attitude towards all observations, extending fields other than electrical. As experience is gained the student uld acquire a feeling for the organization of his experimental work , in the larger experiments, some sense of co-operative activity.
Development of the writing of concise English and the presentation lata in a clear and understandable form.

The successful achievement of these aims depends on:

ction and Design of Experiments.

hese are discussed more fully below.

oratory Instruction Sheets.

hese, together with the personal attitude of supervisors, are oonsible for developing a critical attitude towards the experiments. y should be as comprehensive as possible, and should include a nber of questions to be answered to ensure that the implications he experiment are appreciated, and that the relative importance errors in the different readings are noted; together with addi- al notes explaining why particular items of equipment are used, linking the equipment with others or with future course work. he early part of the course, detailed instructions are only too essary for most students to formulate a reasonable approach and entation. In the later years the instructions should be curtailed.

ort Writing

ne traditional procedure is for the student to take away his experi- tal "results" after taking whatever steps seem necessary to apply ks on their completeness and reasonableness before leaving the ratory, and then to submit after suitable private work, a finished rt. The method has the disadvantage that the student has to do h of his work away from the advice and guidance which he may in interpreting his results.

eally, reports which have been written in the laboratory would to meet these objections. Certain experiments, however, require ature to be consulted and lengthy calculations made. In these umstances, the best compromise appears to be for the student to s much as is practicable before leaving the laboratory. This ratory record, duly checked and initialled by the instructor before tudent leaves the laboratory, is then submitted, together with any tional work which is done later, as a final report.

is worth impressing upon students the degree to which a carefully tated diagram can express concisely the experimental conditions procedure.

ratory Organization

typical elementary electrotechnics laboratory may cater for 15–25 os of students. With the numbers involved, it would be impos- even if it were desirable, to allow the students to choose their own s, etc., and formulate their own procedure. This practice may advantages where small numbers are concerned and generous vision is possible, i.e. in later stages of the course, but it leads to unfinished experiments, unchecked errors and too much unproductive blundering during the early stages where students are unfamiliar with equipment.

Supervision

Supervision of elementary laboratories is difficult as it tends to be an unpopular staff duty, which then devolves upon young demonstrators. This may appear to solve the staffing problem, but such supervisors do not always take the critical viewpoint which is necessary, they change frequently so that there is no continuity, and they may have no responsibility for assessing the students. Senior staff who take such duties seriously give a valuable service.

"Original Work"

Little of this is possible during the first two years of the course. To encourage students during this period to think of the type of equipment to choose, and the method of approach to problems, they can be asked to design experiments, on paper, to illustrate certain topics or verify experimental laws, specifying fully the type of meters and other equipment required and the handling of the results.

Selection of Experiments

One of the problems throughout the course, but particularly at the start of the first year, is that of students undertaking laboratory experiments before the relevant theory has been covered in lectures. A lecture may be easier to assimilate and possibly more interesting to a student who has encountered the problem in practice, but many experiments cannot be performed properly without a knowledge of the theoretical background, and that cannot always be condensed sufficiently to appear on an instruction sheet.

This difficulty can largely be overcome, and the interest in what may be termed "experimental method" aroused, by commencing the laboratory work of the initial year with experiments requiring only an elementary knowledge of d.c. circuits, but requiring observations on the accuracy of the meters used, the scatter of observations, linear and non-linear relationships, curve-fitting and the use of logarithmic graph paper, and simple energy considerations. These may occupy the first ten weeks whilst the lectures are covering fundamental theory. A fuller treatment of experimental method, considered as the study of the factors governing the design of experiments and the analysis of experimental results, is appropriate to a later stage of the course, in the measurements laboratory.

Subsequent to the special arrangements for the first few weeks, the choice of experiments is governed by (*a*) *suitability*—simple experiments calling for little ability from the students lead to loss of interest and should be avoided. Such experiments, howevery, have their uses when emphasis is to be put upon the numerical analysis of results; (*b*) *practicability*—experiments must be so arranged that, in competent hands at least, they perform satisfactorily, and it is then possible to point to incompetent hands, and not unsatisfactory equipment, as the source of error.

There is no doubt that greater use should be made of demonstrations both in the lecture room and in the laboratory, as a supplement to formal experimental work. Besides the stimulation which such demonstrations provide, the student can be introduced to a number of topics or illustrations which would not merit treatment as formal experiments.

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A certain amount of time devoted to examination of and reports on equipment, fault location, elucidation of circuits and the production of schematics from such experiments, is not out of place.

It is commonplace that the field of study included in Electrical Engineering has been and is expanding at a remarkable rate. The increased range and content of the science can be met to some degree in lecture courses, by placing increasing emphasis on systematic and generalized treatments. There is a counterpart to this action, in laboratory work, in the introduction of experiments to illustrate and investigate generalized topics such as, for example, circuit theorems, field distributions, and elements of control systems, etc.

In the face of an ever-increasing volume of material calling for inclusion, traditional laboratory experiments must be constantly examined for justification. In the earlier days of the science when the subject was less extensive, experiments were performed which to-day may be found to be either redundant or lacking in basic scientific value. The older branches of the science, e.g. electrical machinery, are often the most in need of such attention.

Apart from the demand of new material for inclusion, the possibility should always be borne in mind that existing and basic material may not be adequately treated. In spite of the large proportion of laboratory time given in many courses to electrical machinery, it is probable that such basic phenomena as commutation, armature reaction and the idea of the machine as an amplifier are often inadequately treated experimentally in the early stages.

Design of Experiments

Very little apparatus, except for standard measuring gear, is commercially available in the most suitable form for electrical engineering laboratories. There is almost limitless scope for ingenuity in the design of good experimental layouts.

Certain standard electrical machines are more or less suitable in their commercial form, but even in this field the special requirements of an educational institution often call for special designs. Such requirements include electrical ratings to conform to laboratory supplies, special characteristics, the addition of search coils and thermocouples, and facilities for driving or loading.

Even when no modification of an existing experimental equipment seems necessary, it will often be found that the experimental procedure can be revised with advantage. Students should not be asked, for example, to repeat a series of operations at a number of different loads, speeds, voltages, etc., unless some really significant result is thereby illustrated.

Electrical machinery and a few other applications excepted, one usually has to begin a design of an experiment *ab initio*.

Briefly, equipment for use in electrical engineering instructional laboratories should as far as possible possess the following features:

Clear exposition of the essential principle it is designed to elucidate.
Educational value in stimulating insight and experimental facility.
Time-saving: not burdened with non-essential manipulative difficulties.
Modern in technique and design.
Good quality, reasonably "student-proof," and capable of proper maintenance.

Simplicity is important, particularly in the elementary stages. Students should not be confused by an unnecessarily bewildering array of apparatus whose function is far from clear. Cle layouts, ample labelling of apparatus in respect of rating polarities, etc., are essential. It is important to subordina auxiliaries so that they do not overshadow the essential apparat in complexity, operational difficulty or size. Suitable relations ar perhaps unconsciously, fulfilled in machine and large-scale pla tests, but they become more and more difficult to realize in benc experiments.

Whilst the exercise of connecting up apparatus is valuable, can assume too great an importance. There are certain exper ments where a clear mental view of the essential circuit througho the experiment justifies the use of permanently connected equi ment, particularly if this can be associated with a semi-pictori layout. The use of models, besides illustrating a much-use engineering technique, often permits the justifiable exaggeratio of certain significant phenomena. How far a model techniqu may be justified if secondary phenomena are thereby modifie is a matter for careful consideration.

The application of the more recent measurement technique to older branches of the subject should be considered. Electric machinery laboratories have tended to be inhabited only b voltmeters, ammeters and wattmeters. There are signs, how ever, that electronic devices and a.c. bridges and potentiomete are finding useful application here. Apart from their value a instruments, it is good for students to see the inter-relation of th various branches of their studies.

Laboratory Design

Surroundings which are not only technically suitable but als attractive and workmanlike in appearance assist in providing th right atmosphere for the efficient performance of experiment work. The opportunity to design the laboratory building itse seldom arises. When it does, the ideal arrangement appears t be a room with as much unbroken lower wall space as possibl

Arrangements for electrical supplies to the work benches shoul be flexible but not extravagantly elaborate. The wiring shoul however, be planned so that no additions in the form of unsightl temporary wires are needed as far as can be foreseen.

Benches should provide adequate storage space for portab equipment in cupboards and drawers. It is desirable to have certain proportion of plain benches under which wheele apparatus can be placed, or with a single low shelf for th storage of the larger electronic test units. It may be possib to arrange for tables carrying permanently connected assemblie e.g. potentiometers, to have false tops to permit normal use the tables for other purposes.

Conclusion

Whatever the material facilities provided for the student, h effective development as an electrical engineer, particularly the experimental field, will be determined largely by the enth siasm of the staff concerned. As has been mentioned earli the work of those members of the staff who take seriously th design, development and operation of laboratory facilities is the greatest value. Such work should command the respe which it deserves and should not suffer in academic rega relative to other activities. Not only does it contribute in measurably to the education of the student, but it forms o of the best channels through which assessment of the studen abilities may be made. In general, insufficient use is made such opportunities for assessment.

Abstract No. 1820
Feb. 1955

SOUTH MIDLAND CENTRE: CHAIRMAN'S ADDRESS

By A. R. BLANDFORD, Member.

"SYNOPSIS OF POST-WAR SCENE OF SOME ASPECTS OF POWER ENGINEERING"

(ABSTRACT *of Address delivered at* BIRMINGHAM, *4th October*, 1954.)

[The theme of this Address is the increasing consumption of ...ctric power and the extreme urgency attaching to efforts that ... and are being made to economize in our dwindling coal ...plies.]

The theme of this Address is the increasing consumption of ctric power and the extreme urgency attaching to efforts that 1 and are being made to economize in our dwindling coal plies.

Mining

The total horse-power of $6\frac{1}{2}$ million in use in the mines to-day is l rising, and while this may increase the fuel consumption in power stations, it is a favourable exchange, as in 1953 the wer stations sent out 6% more electricity for only a $3\frac{1}{4}$% rease in coal consumption.

Broadly, increased outputs have been obtained by improvents in mining machinery, for cutting, slotting and ploughing l by a new form of plastic belting for carrying the coal on all the steepest gradients. The belting is run continuously at a nstant speed and so ensures that associated installations operate optimum capacity. For haulage purposes, Diesel locotives with modified exhaust systems to comply with safety ulations and flameproof battery locomotives are being used. e low maintenance cost of the latter may well determine the ure of underground haulage. A trial overhead trolley-wire omotive installation $1\frac{1}{2}$ miles in length working at 220 volts s installed by special permission of the Ministry of Fuel and wer, and this has been working successfully for approximately elve months. Other improvements include the extraction of damp from the strata for driving dual-fuel Diesel engines, installation of v.h.f. radio telephones for use in emergency, l increased sizes of fans up to 3 000 h.p. for improving ventila-n for working further inbye.

For the transportation of coal, material and men through the ft, the electrically-driven winding engine is now universally pted and the Ward Leonard drive, much favoured for its plicity of operation, is now seriously being challenged by the drive, combined with controlled compensated d.c. dynamic king, on the score of lower first cost. Both are equally suited automatic control, which is so necessary for working to scribed speed cycles, increasing the winding capacity and ucing liability to accident through human error. The cost of nning old colliery generating plant is indefensible, and it is gested that the gas turbine should provide the answer, in the ure, for the production of power and heat where there is ficient supply of cheaper low-grade fuel.

n spite of all these improvements grave doubts exist whether l will ever again be produced in sufficient quantity to maintain position as the second largest exporting nation in the world. e fact that we are already importing coal emphasizes this ntry's great need and desperate urgency for another source heat in the form of atomic power, and sincere hopes are ressed for the fulfilment of the Government's intention to ply more than 50% of our electric power from this heat rce by the turn of the century.

Steam Turbines

Vith the total generating capacity of this country now exceed- 19 million kW, the size of units is being increased from 100 120 MW for commissioning in 1957 onwards, to be followed r by units up to 200 or even 250 MW, and work is already well advanced on designs up to 200 MW. This increase in size demands higher steam pressures and temperatures and so adds to the problem of getting the steam into and out of the machine. Where the steam enters the high-pressure end, the solution is partially achieved by increasing the pressure to reduce the specific volume, but higher pressure means increased temperature to reduce wetness of steam at the low-pressure end. The consequent increase of volume is offset by increased thermal efficiency, leading to a reduction in total quantity of steam required.

The problem at the low-pressure end of the turbine is to pass the large volume of steam out at a reasonably low velocity, and cross-compounding which takes the form of a high-pressure turbo-alternator running at one speed and its exhaust steam crossing over to a separate low-pressure turbo-alternator running at a lower speed considerably facilitates this. Double-flow low-pressure casings, dividing the volume of steam into two separate paths, have been used for years for machines of 30 MW and upwards, and now with the reduced steam rates from higher cycle efficiencies due to higher steam conditions and reheat, turbines can be built with a double flow for ratings as high as 150 MW, but for higher outputs the number of flows must be increased. Reheat implies returning the steam to the boiler and thereby nearly restoring its temperature to the original value, and by this means obtaining 4% or an even higher improvement in overall thermal efficiency.

Alternators

Hydrogen cooling has enabled the alternator to keep pace with the increase in the size of prime mover without exceeding the limits of the physical dimensions and weights of forgings. Hydrogen provides superior thermal conductivity and rate of heat transfer from hot surfaces, and since its density is only about 12% of that of air, the windage and fan losses are reduced, with a substantial overall increase in efficiency. The bold conception of utilizing a potentially hazardous gas for cooling has been fully justified, and its use is now generally accepted for machines of 60 MW rating and above. Further increases in output have been obtained by raising the pressures from the initial value of $\frac{1}{2}$ lb/in^2 to 15 lb/in^2, and now a number of machines are working at 30 lb/in^2, increasing the ratings by 25% above that obtainable from hydrogen at atmospheric pressure, and making it possible to manufacture and transport alternators up to about 150 MW. For the larger units, 200 and 250 MW, it is necessary to resort to a basically different system, aptly described as "inner cooling." This employs the underlying principle of removing the heat losses by passing the cooling medium through and in direct contact with hollow rotor conductors. A similar method is also used for cooling the stator. By this means it is possible to obtain twice the output from the same active material used in conventional present-day designs.

Transformers

Stress is laid on the advantages of improving the magnetic material to obtain larger flux densities, leading to a saving in material and smaller size. This is exemplified by the development of oriented steel by a cold-rolling process, simultaneously improving the permeability and core loss, enabling higher densities to be used without increasing the magnetizing current.

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It is hoped that still further advantages will be obtained by better rolling techniques and control of impurities and more effective heat treatment.

Insulation techniques have kept pace with the increasing voltages, and by the use of cathode-ray oscillographs with surge generators it has been possible to measure and analyse stresses created by impulse voltages. This research has resulted in improved methods of winding to prevent local concentrations of stress and so to increase the ability of the transformer to withstand the effects of lightning surges, and, providing due care and attention are given to oil-filling to prevent inclusion of gases, a dangerous source of weakness to impulse strength is eliminated. Non-inflammable liquids are not in general use except for particular applications where the fire hazard involves special risks.

In this country, Buchholz protection responsive to generation of gas within the transformer has been successfully used, but this form of protection is not applicable to transformers incorporating gas sealing by nitrogen, which practice is in general use in America. A few transformers of this type are also in use in this country. Some designs provide a large expansion space for the gas, allowing the pressure to rise and fall with temperature, and others include a compensating device which substantially maintains constant gas pressure.

Transformers with oil-impregnated paper bushings have been built for 400kV, and it is expected that transmission requirements will increase this to 500kV.

Switchgear

For the higher voltages, say 132kV and above, the user is still faced with the problem of selection from the conventional oil, the oil-minimum, and the air-blast circuit-breaker, and it is expected that the successful Bonneville tests on air-blast circuit breakers may influence American designs in the future. For voltages of 230kV and above, the oil-minimum and the air-blast types may easily become the generally accepted standard.

For voltages up to 30kV, the oil circuit-breaker is in general use in this country, whereas in America, up to 13·2kV, the practice has changed to air-break circuit-breakers in a remarkably short space of time; this trend is also extending to Canada. The testing of circuit-breakers in this country has been developed to a much greater extent than anywhere else in the world, and the wisdom of this is open to question, particularly as foreign buyers point out that the preponderance of their troubles with circuit-breakers, although only rare, are due to mechanical or electrical failure and are in no way connected with ability to clear short-circuits.

Based on the experience that faults are usually "self-healing," auto-reclosing, widely used in America and on the Continent, has enabled these countries successfully to conserve on parallel feeders with little inconvenience and loss.

Transmission

The future trend of transmission has become obscured by the introduction of a d.c. system now working in Sweden, the use of series capacitors for long-distance a.c. transmission and the possibility of electricity being produced from atomic power.

It has been said that the increase in the population of the world at a rate of 25 million per annum, combined with the increased use of electricity per head, compels the generation of hydro-electric power for d.c. transmission over unlimited distances. Interpreted literally, this could mean that power to this country might be supplied from Russia or the Himalayas, but the wisdom of this is doubtful under present world conditions. However, series capacitors are extending the range of a.c. transmission, and the possibilities of power from atomic-energy heat sources would seem to offer attractive alternatives to the solution of this problem of world power shortage. Series capacitors also possess the advantage of improving "stability," assisting in minimizing voltage drop when load switching, and balancing line reactance to control the division of current in parallel lines, etc.

It is also possible that in this country we have not made sufficient use of auto-reclosing for shortening overhead earth-wire protection to, say, $1\frac{1}{2}$ miles from power stations and sub-stations, and so effecting a considerable saving in cost. In lightning areas this may result in more outages, but these would only be momentary, say some 20–30 cycles, creating little or no disturbance, and at the same time the power station and sub-station equipments would be safeguarded.

Traction

Electrification of the railways offers excellent opportunities for saving fuel, as by this means some 8 million tons of coal could be saved per annum with an increased demand for the power stations of only about 2·6 million tons of a lower grade. America sets the example; for, with her plentiful supply of oil, she has practically changed over to Diesel-electric traction.

In this country, manufacturers of electric traction equipment have concentrated almost entirely on d.c. equipment up to 3 000 volts with mercury-arc rectifiers in trackside substations, but more recently interest has centred on a single-phase system with the rectifier equipment transferred to the locomotive, and such a scheme has been operating in this country for some time now with every success. This enables operation at voltages up to 25kV at industrial frequencies, thus effecting considerable economy in fixed installations such as substations and other trackside equipment. It also has the advantage of using standard d.c. motors and control-gear.

Application Engineering

More recently there has developed a new kind of industrial conception known as "continuous flow," exemplified by automobile factories where conveyor operations work continuously to secure optimum output.

Another outstanding case is the steel industry, where attention has been concentrated on improving the rate of response, enabling the reversal of a 30 000h.p. motor to be accomplished in one second from base speed to base speed. Spectacular achievements have been made on strip tandem mills, now raising the speed from 800 to 2 200ft per min; progress has been much the same for rod and bar mills, where, for the heavier type, speeds have reached 2 500ft per min and for lighter bars 5 000ft per min rolling 2, 3 or 4 rods simultaneously.

The achievements would be ineffectively utilized if it were not for the auxiliaries which feed the material into the processing machinery—handle it between operations and transport it away for finishing, cutting up, packing and shipment. In fact, materials handling can account in some cases for 30% of the total manufacturing cost and may possibly show a greater gain in production than by speeding up the processing machinery.

To summarize: I have emphasized the continuous efforts being made by the manufacturers to improve efficiencies and so to conserve our dwindling supplies of fuel. Coupled with this is the urgent necessity for an alternative fuel to meet the increasing consumption of electric power, as the factors causing this are more than ever still at work. As the industry grows its problems grow with it—higher voltages, high concentrations of power, better protection and improved distribution. In the past the users and the manufacturers have worked together, and they will continue to do so in the solution of their future problems; and also, by the presentation of papers with encouragement to discussion, The Institution has already contributed much to the phenomenal development and growth of our industry.

Abstract No. 1829
Feb. 1955

SOUTHERN CENTRE: CHAIRMAN'S ADDRESS

By E. A. LOGAN, M.Sc., M.I.C.E., M.I.Mech.E., Member.

"IS THERE A FORESEEABLE LIMIT TO THE DEMAND FOR ELECTRICITY?"

(ABSTRACT *of Address delivered at* PORTSMOUTH, 6*th October*, 1954.)

Each stage of expansion of the electricity supply industry has had its peculiar difficulty. The immediate problem which concerns us to-day is fuel; a second problem is finance.

Regarding the first problem of fuel supplies, there has been much speculation concerning the application of nuclear energy to the generation of electricity. The most recent and most authoritative quotation I can trace is that of Sir John Cockcroft, who said that nuclear power could make an effective contribution to filling any gap which might arise in the next 20 years between our energy needs and supplies at a cost only slightly above that of conventional power.

One may note some tendencies of current thought:

(i) Supplies of heavy fissionable elements are less restricted than early pessimism suggested.

(ii) The wildly optimistic and equally pessimistic views on cost meet on a more rational plane—a cost only slightly above that of conventional power.

(iii) The exploitation of nuclear energy will be through the medium of electricity generation and distribution systems. Alternatives of small power packaging and development may appear, for example, for transport or for space heating. So far, they have not been disclosed in forms suitable for private civilian use, and it may well be that the technical and cost aspects may effectively delay their development.

Up to the present, the increase in demand has amounted to some 7% per annum, resulting in a doubling of sales of electricity every 10–12 years. Increase in demand has resulted from the two causes: (*a*) connection of new consumers, and (*b*) increase of consumption by existing consumers. Of these, (*a*) has increased by the penetration of new distribution to take on additional premises, and (*b*) has increased by an extension of use, resulting from greater availability of new types of apparatus. Total demand resolves itself into the product of these two factors, number of consumers and average demand per consumer.

Much speculation has taken place as to population trends,* but we may perhaps be forgiven if we do some simple extrapolation. We may finally err as to the dates of occurrence of population levels, but fairly certainly, barring major disasters which would invalidate more than the forecasts of this Address, we may be sure that certain population levels will be reached at about the time suggested, and we are more concerned with levels than with the precise dates at which these levels are reached. Fig. 1 shows the trend of population compared with the number of connected consumers of electricity. It is well known that the great majority of town houses are now connected to electricity mains, and the connection of rural premises and new housing estates is progressing rapidly. Looking at the graph, and particularly the line marked "Population/3," it seems reasonable to forecast that, at a time as near in the future as eight years from now, the total of consumers should be reaching a ceiling and that new connections will be substantially balanced by disconnections of demolished property. The ratio of 3 is a usual urban ratio of population to consumers.

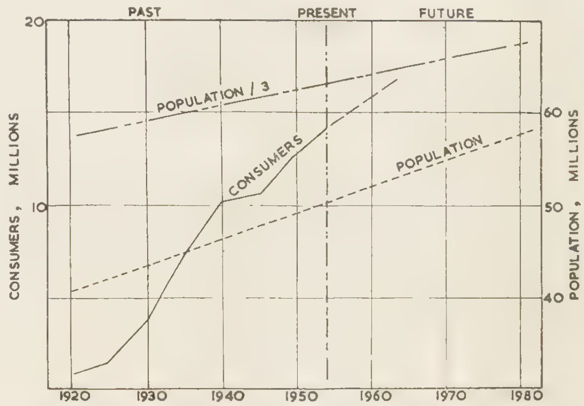

Fig. 1.—Consumers and population.

The next factor to ascertain is the foreseeable limit of consumption per person. Each member of the population, whether at an office desk, in a factory or at home, requires light, heat and power in some form or another, and the recent tendency has been to transfer many of these requirements to electricity. So far as the individual is concerned, convenience and price are the factors which determine the choice. Conservatism tends to slow down the rate of change, even when economics indicates that change is desirable. On the other hand, desire on the part of large numbers of the populace to be in the fashion, to appear up-to-date, may speed up a tendency, even against adverse economic factors. Under present conditions, economic factors greatly encourage the extension of the use of electricity for substantially all heat and power requirements. The major source of heat in this country is coal, and it is appropriate at this point to look at the figures relating to the use of coal in this country as given in the Ministry of Fuel and Power *Statistical Digest* [1952, page 86, Table 62 (B)]. We can use these figures of coal consumption to form an estimate of the probable extent of total consumption of electricity by assuming that heat and power requirements increase in proportion to the population, and that one kilowatt-hour of electricity can be substituted for 1·3lb of coal and give the same terminal satisfaction. Neither of these assumptions may be altogether true; nevertheless the answer obtained should be of the right order.

Clearly, not all these present uses may be expected to change over to electricity, but col. 5 is an estimate of the possibilities. On this basis the present internal consumption of coal of 210 million tons per annum may possibly be modified to some 80 million tons for purposes other than the generation of electricity, with the balance supplied as 260 000 million kWh of electricity.

It is interesting to check this total by making a forecast of the probable use likely to be made by an individual to meet his

* PUTNAM, P. C.: "Energy in the Future" (Macmillan and Co., 1954), Chapter 2.

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Table 1: Hypothetical Substitution of Coal by Electricity for a Population of 55 million Persons

1	2	3	4	5	6
Use	Coal	Electricity	Units per head of population (49·5 M)	Probable use of electricity per person	Balance as coal for population (55 M)
	tons × 10⁶	kWh × 10⁶	kWh	kWh	tons × 10⁶
Gas supply	27·435	47 300	964	64	28·80
Electricity	35·785	61 600	1 242	1 242	—
Railways	13·908	23 900	484	84	12·80
Coke ovens	26·408	45 400	917	450	14·90
Industry	42·981	74 000	1 496	1 200	9·45
Domestic and miners' coal	38·425	66 200	1 338	1 338	—
Collieries	10·154	18 200	368	368	—
Miscellaneous	11·413	19 600	396	—	12·65
				4 746	78·60

reasonable needs; it is assumed that he will not greatly change his habits over the years and, in particular, will not insist on heating his living and working spaces above the comfort level now regarded as acceptable in this country:

Table 2: Units per annum per Person

	kWh
Cooking—1 kWh per person per day ..	350
Water heating..	1 000
Refrigeration	100
Space heating	2 000
Transport	100
Lighting	120
Manufacturing	1 000
	4 670

The two estimates, arrived at by quite different routes, substantially agree. It would seem, therefore, that a population of 55 million is likely to consume some 250 000 million kWh of electricity per annum—rather more than four times the present amount. Thereafter the rate of increase is likely to be greatly reduced and to move in step with the trend of population.

The possibility of unlimited expansion of the use of electricity is herein specifically rejected. Briefly, the grounds for this are that a consumer will use electricity only to satisfy his reasonable requirements. The large expansion in the use of electricity up to the present has resulted from the substitution of electricity for other methods of developing heat and power. A great extension of the average consumer's need for heat and power cannot be envisaged, particularly in the face of progressively improving efficiencies of utilization, and the present review is, as has previously been stated, based upon substitution of electrical methods for satisfying established needs.

Growth of demand for goods or services follows a fairly well established course, as shown in Fig. 2. This consists of three zones which represent the period of introduction, general acceptance and saturation of demand. This applies to most articles or services, e.g. breakfast foods or wireless sets. The application of this type of growth-of-demand graph to the development of electricity supply may not be too apparent. It is my view, however, that it does apply and that we are now in Zone B.

Our question, "Is there a foreseeable limit to the demand for electricity?", would, in the light of what has been said, appear to be capable of being answered. The answer suggested is certainly large enough to provide satisfactory occupation for all who are employed in the electricity supply and manufacturing industries for many years to come and also will require the services of a great many in addition. There will, in fact, be a great and continuing expansion, even though an ultimate restriction of the rate of expansion can be visualized. This forecast (Fig. 3) is only an order of magnitude and depends upon maintenance of the present gradual improvement in the price of electricity in relation to competitive sources of power. Any dramatic lowering of the price per unit of electricity in relation to the other

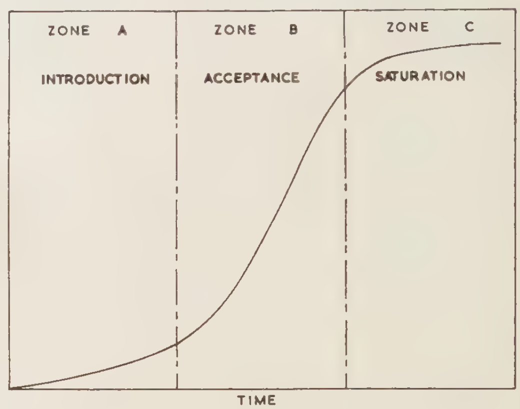

Fig. 2.—Growth of demand.

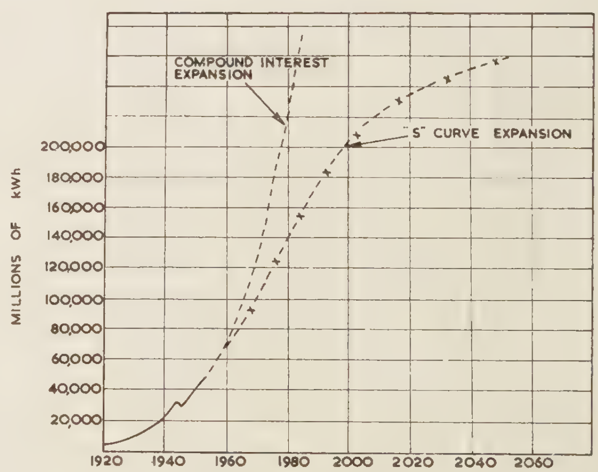

Fig. 3.—Projected expansion of energy sold by electricity supply industry.

sources would greatly accelerate the rate of electrical development and also raise the total demand above that forecast—largely because greatly extended use of electricity for heating would not be controlled by cost and there would be no economic incentive to improve efficiency of utilization.

Abstract No. 1821
Feb. 1955

NORTH LANCASHIRE SUB-CENTRE: CHAIRMAN'S ADDRESS

By J. EATOCK, A.M.I.Mech.E., Member.

"SOME PROBLEMS IN THE DESIGN AND INSTALLATION OF THE AUXILIARY ELECTRICAL SYSTEM OF A LARGE POWER STATION"

(ABSTRACT *of Address delivered at* PRESTON, 13*th October*, 1954.)

The design of a large power station entails many considerations, and much information has been published on the design of the major components. Some of the more minor matters, which are usually overlooked in publications, form the subject of this Address; these fall under the headings which follow.

The station building is a brick-panelled reinforced-concrete structure, housing four 31·5 MW turbo-alternator sets and eight chain-grate-stoker-type water-tube boilers, with all associated auxiliary equipment and plant. Generation is at 11 kV with direct-coupled main transformers, switched at 33 kV. Station auxiliaries are supplied from four 2 000 kVA unit transformers, each directly coupled to its associated alternator, and two 2 500 kVA auxiliary transformers, fed from the 33 kV station busbars.

Auxiliary Supply Feeders—Determination of Current-Transformer Ratio.—In the initial design stages, certain basic decisions were made, such as the location of the main auxiliary switchboard and the auxiliary supply voltage; 400 volts 3-phase was chosen for the latter. It was decided that each unit transformer should supply half of the essential auxiliaries for its associated set, and each auxiliary transformer the remainder of the essential auxiliaries associated with two sets together with common auxiliaries such as coal- and ash-handling plant.

At this stage the schematic for the ultimate development of the main auxiliary switchboards and feeders was drawn, followed by the detailed requirements for the first stage; both these diagrams were laid out to show the approximate relative physical location of the equipment, the latter including all motor ratings and full-load current values.

Protective arrangements included magnetic over-current devices and h.r.c.-fuse fault protection in contactor starters, the settings being chosen so as to avoid tripping under estimated starting conditions and at the same time to give overload and stalling protection. Circuit-breaker-controlled feeders were fitted with over-current and earth-fault relays, current-transformer ratios and relay settings being chosen to avoid operation under starting conditions, and to give fault discrimination.

Curves were drawn showing the several motor starting-current peaks related to estimated starting times and sequence, the resultant envelope being used in each case to determine the current-transformer ratio having regard to maximum starting current and normal full-load current, and also the relay plug setting to prevent operation during the starting sequence.

Effect of H.R.C. Fuses on Cable Sizes.—Circuit-breakers were used for the control of cables feeding essential auxiliaries in order to facilitate restoration of supply following a fault. Other feeders, such as coal and ash-plant feeders, were protected by h.r.c. fuses; this considerably reduced the length of the switchboard, and, owing to the extremely short operating times and cut-off effect, allowed the cable sizes to be related to load requirements without sacrificing fault rating.

Cable Diagrams and Schedules.—The layout adopted showed the correct physical relationship of the plant, at least in plan view, and this greatly facilitated the segregation of the various groups of cables for which tunnels, riser shafts or ducts were required.

Cable schedules, compiled from the cable diagrams, included a column in which the proposed route of each cable was briefly traced. This detailed checking of every route was of great assistance in making proper provision in the building for shafts, bridges or tunnels, and in avoiding expensive cutting of reinforced concrete. The total number of such schedules for the completed station was 21, containing about 1 000 separate items comprising approximately 28 miles of cable of all sizes and types.

Earthing and Bonding.—There were three voltages in the station, namely 33 kV for station output, 11 kV generation and 400 volts for auxiliaries, and since the building was of reinforced concrete a planned copper bonding system was adopted in the interest of safety. To determine the maximum size of bonding conductor required, a formula was developed connecting maximum earth-fault current, maximum duration of fault, permissible temperature rise and conductor cross-section, from which a maximum size of $2\frac{1}{2}$in × $\frac{1}{4}$in was obtained, based on 36 kA, 3 sec and 150°C. Two smaller sizes of conductor were used for branch connections requiring lower fault ratings, and all bonding conductors laid in the ground outside the station were suitably corrosion proofed.

Cable Installation Arrangements.—As the detailed building plans were developed and apparatus positions were fixed, cable "bands" were earmarked on walls and under floors. In all floor beams on these "bands" the architects were asked to provide 1 in-diameter steel tubes, spaced 18 in apart, fixed on the neutral axis of the beams, for the suspension of cable steelwork. With these provisions it was a simple matter to suspend the cable steelwork, and in particular in the main cable passage below the auxiliary switchgear room, to suspend steelwork clear of the floor and divide it into longitudinal runs so that easy access could be obtained to all cable positions both during installation and later for maintenance purposes.

The vertical cable runs extended to nearly 100 ft in certain cases, and cleats were devised consisting of individual saddles and straps bolted on to horizontal slotted cross-members, which, in turn, were set off from the wall but bolted to it. Where large numbers of cables ran together, a double-tier arrangement was adopted to give adequate clearance between cables and at the same time to permit the renewal of any one cable without disturbing the others.

Approximately 30 cables had to be carried across under the turbine-house floor; to provide the required capacity by means of cables in ducts would have needed at least 7 additional cables, and a most cumbersome and costly arrangement would have resulted. A cable tunnel, well ventilated and giving unrestricted access, was provided, the cables being well spaced and supported on wall hangers.

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NORTH STAFFORDSHIRE SUB-CENTRE: CHAIRMAN'S ADDRESS

By J. M. FERGUSON, B.Sc.(Eng.), Member.

"SOME ASPECTS OF HIGH POWER PULSE GENERATORS"

(ABSTRACT *of Address delivered at* STAFFORD, 11*th October*, 1954.)

The general arrangement of an impulse generator, shown in Fig. 1, consists of the following units: a *supply*, capable of delivering all the energy required by the pulse generator as a

Fig. 1.—Basic scheme for pulse generator.

steady load; a *store*, into which the supply feeds, and taking one of several forms discussed later; a *convertor*—the energy stored need not be electrical, and as high-energy electrical impulses are being considered the store is coupled to the load by a convertor to convert the energy to an electrical form; a *switch* which controls the discharge into the load at the appropriate instant; if the whole energy is not to be used for each pulse, the switching device must be capable both of a making and a breaking duty.

Energy Store.—Any type of energy store can be used, provided it is capable of repetitive cycles.

Five practical types of store which are used in a number of pulse generators will be examined: potential mechanical energy, dynamic energy, electromagnetic energy, electrostatic energy, and electrochemical energy.

considerable losses which could be reduced by running eithe in a vacuum or in hydrogen, but the increased complications ar not often considered worth while. For short pulse lengths, th only satisfactory store is electrostatic.

Switch.—Conventional contactors for circuit-breakers exist t meet most conditions where low repetition and long pulse rate are involved. Air-break and air-blast types are the most likel to withstand heavy duty.

Special consideration has been given to making and breakin devices which has enabled mechanical switches to be develope that will carry out switching operations at repetition rates c 50 times per second with capacities of several thousands c amperes. These switches are used in a mechanical rectifier.

For high repetition rates, high-vacuum triodes can be usec but the maximum voltage is limited by the emission of the filamer at the peak voltage that the valve will withstand.

Gas discharge devices of the following different types hav been used: hot-cathode gas discharge valves, spark-gaps, colc cathode diodes, and mercury-pool valves. The appropriat characteristics of each of these types of switch are discussed.

A further type of switch consisting of a saturable iron-core reactor can be used. High powers with short pulse lengths hav been reached with this type of device.

Table 1

Type of energy store	Volume efficiency		Duration of pulse discharge		Storage losses	Remarks
			Max.	Min.		
	ft-lb/ft³	joules/cm²			watts/ft-lb	
Potential mechanical	$3 \cdot 12 \times 10^3$	0·15	Hours	Hours	Nil	Based on water storage
Dynamic	$5 \cdot 0 \times 10^5$	24	Seconds	Milliseconds	$6 \cdot 0 \times 10^{-4}$	—
Electromagnetic ..	250	0·012	Milliseconds	Milliseconds	30	Losses based on 10 millisec
Electrostatic ..	$1 \cdot 15 \times 10^3$ 20·5	0·052 0·001	Hours	Microseconds	Very low	Impregnated paper condensers
Electrochemical ..	$1 \cdot 6 \times 10^6$	78·5	Hours	Seconds	Very low	Planté cells

The following characteristics of these types of store, summarized in Table 1, are considered: space required for a given unit of energy stored, suitability for particular pulse length, and storage losses.

Of these types of store the most efficient for its size is the electrochemical store, but unfortunately, owing to high internal impedance and polarization effects, short-time currents are severely limited. The 3-sec rating is normally not greater than 22 times the 10-hour rate of current discharge, although high-duty cells can be obtained in which this is very significantly increased.

For medium pulse lengths, the most generally used store is a rotating mass such as a flywheel or rotor. This gives rise to

High-Power Pulse Generators.—Pulse generators can be used i the following general ways:

Where the load fluctuates rapidly, as in rolling mills.

Where conditions caused by the release of a single high-power puls of energy for a short time are to be investigated, e.g. particle accelera tion, cloud chambers, short-circuit testing and high-voltage impuls testing.

Utilization of echo techniques for producing a high-power burst c radiation.

The design of one example of each type of generator is con sidered in relation to the fundamental characteristics outlined i the Address. For this purpose, the design of a hot reversin mill, a short-circuit testing plant and a pulse generator for rada using a mercury-pool modulator valve, are considered.

Mr. Ferguson is with the English Electric Co., Ltd.

Abstract No. 1823
Feb. 1955

RUGBY SUB-CENTRE: CHAIRMAN'S ADDRESS

By D. EDMUNDSON, B.Sc.(Eng.), Member.

"THE CHANGING OUTLOOK IN ELECTRICAL MEASUREMENTS"

(ABSTRACT *of Address delivered at* RUGBY, *5th October*, 1954.)

A singular feature of present-day electrical engineering is the ncreasing emphasis on mathematics, not only as a necessary basis, but as a practical tool, for the solution of specific problems. Fifty years ago, when electrical engineering in Rugby was in its nfancy, the mathematical basis of electrical machine design was being worked out by such men as Dr. Carter, who produced a complete solution of air-gap field problems, and Field and Taylor, who worked out solutions of the problem of eddy-currents in stator windings. In those days, experimental echniques were inadequate and many of the components on which we now depend for measurement work did not even exist; but to-day the position is entirely changed. It is difficult to point to an example of a measurement problem in electrical engineering which is incapable of solution in a practical, convenient and reliable way.

In the belief that this striking change in the possibility of measuring quantities only capable of mathematical estimation in he days of the pioneers has not been realized by many engineers, hree simple examples were illustrated, with demonstrations.

Measurement of Torque.—In the year 1906, long before the ntroduction of conventional torque-meters, an interesting proposal was made by Mr. A. P. Young. He pointed out that he instantaneous value of the rate of deceleration of the rotor of a machine—a quantity required in the course of testing—could be obtained directly in a simple manner. A d.c. generator driven by the shaft could produce a voltage proportional to speed, so that the rate of change of this voltage would be proportional to that of angular velocity, and hence to torque. This quantity Young proposed to obtain either by applying the voltage o a condenser, whose charging current would be its derivative, r by deriving from it a current to be passed through the primary winding of a mutual inductance; the secondary voltage would hen be proportional to deceleration. Young actually attempted he method, but was unsuccessful only because instruments of the ecessary sensitivity did not exist. Many years later, Dannatt nd Redfearn used the same principle to measure the accelerating orque of an induction motor. Having now available both the alve amplifier and the Duddell oscillograph, they produced ighly successful torque/time curves. Finally, a demonstration vas given of the torque/speed curve which can be obtained using cathode-ray oscillograph. Thus, a complete solution of what vas an intractable problem 50 years ago has been obtained by nodern measuring techniques.

Measurement of Angular Velocity.—Although for many years eliable tachometers have been available, these have had two nain drawbacks. None has been capable of high precision, and ll have imposed a load on the driven shaft which is unacceptable or light-power motors. The first condition was met during the late war by adapting the principle of Maxwell's commutator bridge, which was demonstrated. Long neglected because the apparent complexity of the traditional expressions for balance were considered to render it approximate only, the method is capable of high accuracy in an indicating instrument. This was achieved using components which had been available for many years; but its practical realization as, effectively, a pulse-counting device made its direct application to various forms of drive a simple matter. Using a magnetic pick-up and amplifier, speed can now be measured provided only that a shaft has some magnetic irregularity; failing even this, a photo-electric cell and amplifier can convey to the tachometer pulses derived from black and white markings. It is therefore easy to measure angular velocity with the highest precision without imposing any load whatever on a rotating shaft—another achievement which was out of the question 50 years ago.

Measurement of Temperature.—As a final example, the use of thermocouples presents a further interesting demonstration of the change brought about by modern techniques. Until recently, their use at moderate temperatures was restricted to permanently installed, carefully engineered installations, or delicate null-methods, by the small value of the e.m.f. produced. This was insufficient to operate robust, portable instruments. A development of the potentiometer led to the negative-feedback chopper amplifier. In this, d.c. amplification is achieved by converting the d.c. signal to a.c. by mechanical means and reconverting it after amplification. The function of the amplifier is then to compare the e.m.f. from the thermocouple with that produced by the amplifier output current in a fixed resistor, and to ensure that there is negligible difference between them. This instrument is now portable, robust and accurate; indications are obtained as quickly as a d.c. ammeter can be read, while the resistance of the leads has no effect on the indications. Temperatures can be obtained from a variety of points in quick succession, and couple wires can be so thin that they do not abstract heat from materials of poor conductivity.

These examples, few as they are among a multitude which could have been chosen, may serve to illustrate the difference between the approach to practical problems which is now open to the electrical engineer and that to which his predecessors were confined. How is he to take advantage of the new measuring techniques? Although measurement and instrumentation specialists are essential to their development, it is necessary for the man himself whose problem is to be solved to grasp the methods which are to be used, or he will never appreciate their limitations or possibilities. It is therefore the task of those of us directly concerned with measurement work to encourage our fellow-engineers not only to make use of our new ideas, but themselves to undertake the practical solution of measurement problems which may arise in the course of their work.

Mr. Edmundson is with the British Thomson-Houston Co., Ltd.

Abstract No. 18
Feb. 19

SHEFFIELD SUB-CENTRE: CHAIRMAN'S ADDRESS

By F. L. PARKIN, B.Sc.(Eng.), A.M.I.Mech.E., Member.

"TRENDS IN STEELWORKS ELECTRICAL EQUIPMENT"

(ABSTRACT *of Address delivered at* SHEFFIELD, 20*th October*, 1954.)

A steelworks engaged in the manufacture of heavy cast ingots, which then pass through the various stages of primary and secondary rolling and/or forging, can be classed as a *large* industrial consumer of electricity, having a load of 15 to 30 MW. The works with which I am associated takes a bulk supply from the local Electricity Board, the distribution system comprising:

(*a*) 6·6 kV, radiating from a 19-panel duplicate-busbar metal-clad switchboard of 150 MVA rupturing capacity, and fed from two 15 MVA 33/6·6 kV transformers, the property of the Board.

(*b*) 11 kV, in course of development which will employ an 11-panel board of similar design, capable of 250 MVA rupturing capacity at 11 kV, and fed from two 15 MVA 33/11 kV transformers.

In contrast to (*a*), however, the 11 kV network will incorporate a series of ring mains, to provide duplication of feed in case of faults.

Of the 98·7 million kWh consumed in 1953, 72½% was used in a.c. power and lighting, and 27½% was converted to 230 volts d.c. for cranes and general works use. The latter involves a 10% conversion loss, or 2·7 million unproductive kWh per annum.

The improved efficiency of the mechanical rectifier, which is meeting a demand for heavy-current a.c./d.c. conversion in the electrochemical trade and has made great strides in Germany since the war, appears to offer attractive prospects in meeting a demand for lower conversion losses. An alternative approach to this problem in steelworks is to dispense completely with conversion plant and to generate whatever d.c. power is needed from steam produced by waste heat.

A steel plant with open-hearth melting shops operating a continuous working week, and with rolling mills working at least 16 shifts per week, offers little scope for improving the load factor, but a lot can be done in bettering the power factor. Static capacitors are in course of being connected across the terminals of all a.c. motors of 100 h.p. and upwards, and where additional correction is needed, capacitors are being coupled to the l.v. busbars at transformer substations, with power-factor relays and contactors for automatic operation. In the heavy rolling mill area, with mill motors mainly wound for 6·6 kV, a synchronous condenser offers some advantage, since the reactive power injected into the system is readily adjustable.

I forecast on this account an increasing demand for synchronous motor drives, and cite the case of a cogging or blooming mill powered by a 6 000 h.p. reversing d.c. motor, which is fed from a 4 000 h.p. slip-ring induction motor with Ward Leonard–Ilgner control. By dispensing with the flywheel in the Ilgner set, and using a 7 000 h.p. synchronous motor in place of the slip-ring machine, better power factor and lower operating costs can be achieved. Against this, one has to contend with greater load fluctuations on the supply mains, but with the increasing capacity of feeders and transformers, this aspect is likely to assume less importance as the years go by, and large primary reversing mill drives with straight Ward Leonard control will make an appearance in this country in due course.

Mr. Parkin is with Steel, Peech and Tozer.

The importance of mechanical handling cannot be ove emphasized, and many improvements have been effected in th design of production cranes and furnace chargers. Steelwork have adopted the new standardized range of 1-hour rated mil type reversing d.c. motors, and except for the smaller horse powers, where, for economic reasons, heavy-current drur controllers are used, contactor control is almost universal.

A trend with "hot cranes" for melting shops and soakin pits, is the introduction of air conditioning of driver's cabs an of the crane contactor houses, while much experimenting ha taken place in improved methods of conveying direct current t cranes, first with tee bars and gravity collector shoes replacin trolley-wire conductors for the heavier-current application notably the down-shop track conductors.

Other interesting and highly encouraging results have bee obtained from the use of self-winding cable reels for feedin current to the moving crab, and for a similar purpose the "curtai rail" method of suspending v.r. cables in concertina fashio along the crane bridge.

[Mr. Parkin demonstrated these various methods with lanter slides, and gave an example of what has been done in remotely cor trolling an ingot chariot which feeds hot material from the soakin pits to the cogging mill ingoing roller table.]

Communications in a steelworks stretching 1¾ miles from on end to the other, and occupying, with amenities, an area c about 550 acres, are of considerable importance, and this subje is one which also offers scope for modern methods.

Post Office telephones, a private automatic exchange wit 330 extensions and an ultimate capacity of 600 lines, and pneumatic conveyor system for internal mail and steel sample involving some 10 miles of air tubes, are relatively commonplac

A standard teleprinter service is available for transmission c typed messages between head office, works and branch office but an ingenious piece of electronic apparatus is employe within the works for transmitting the written message (notabl metallurgical data), between laboratory and melting shops.

A system of industrial communication provides a usef 2-way link by loudspeaker between mill operators, while th carrier-frequency method of providing speech communicatio over the power lines to overhead cranes is an interestin development which is of particular value in melting-shop castin bays.

Radio control has proved beneficial in regulating the move ment of shunting locomotives through a particularly congeste area in the marshalling yards, and 7 locomotives are now equippe with mobile v.h.f. transmitter-receiver sets, with a stationary un located in a 20 ft control tower overlooking the sidings.

Electronic controls are finding their way into the steel industr Photo-electric cells are in successful use for automatic control c outdoor lighting, and will find increasing application for grou switching of indoor lighting. The lead-sulphide cell has gre possibilities for control operations with hot material, where th radiant heat emitted from hot steel (instead of the "light source of the photo-cell) hits the sensitive surface of the cell.

Abstract No. 1825
Feb. 1955

SOUTH-EAST SCOTLAND SUB-CENTRE: CHAIRMAN'S ADDRESS

By E. O. TAYLOR, B.Sc., Member.

"THE CONFLICT OF THE SYSTEMS"

(ABSTRACT *of Address delivered at* EDINBURGH, *5th October*, 1954.)

Before proceeding to the main part of this Address I wish to refer to an aspect of technical education relating to the practical training of electrical engineers in Scotland. It is, quite rightly, customary for graduate engineers to complete their training by a two- or three-year apprenticeship with a large manufacturing firm. Most Scottish graduates go to England for this purpose as there is no individual firm in Scotland that is sufficiently large to give a training of the scope generally considered desirable. There is, however, in Scotland as a whole, an unsurpassed wealth of engineering skill and experience, which, if suitably harnessed, could provide a practical training at least equal to that of the major English firms. I suggest, therefore, that by the co-operation of a group of firms, a Scottish Training Scheme could be organized; its trainees would spend appropriate periods with each of a number of firms, and, to give cohesion to the scheme, would gather together two or three times a year for a few days of lectures and discussion. While not supplanting existing courses, such a scheme would offer an alternative having a wider and less specialized scope and should therefore attract not only Scottish graduates but also some of the best graduates from England and oversea. There is no reason why a Scottish engineering training such as that suggested should not carry, in the markets of the world, a reputation equal to that carried by Scottish engineering products.

The main part of this Address refers to the rivalry between the a.c. and d.c. systems for the supply of electrical energy and the battles that have been, and are being, fought over this problem on various fields, particularly the fields of distribution, traction and long-distance transmission.

Distribution engineers were, in the early days (1880–90), faced with the problem of distributing the fairly heavy currents necessitated by the low voltage (100 volts) of the recently-invented Swan filament lamp. Engineers favouring alternating current, headed by Ferranti, solved the problem by distributing at about 2kV and using transformers to step the voltage down at the consumers' premises; d.c. engineers, headed by Crompton, preferred the 3-wire or 5-wire system, which permitted distribution at 200 or 400 volts while still retaining 100 volts for the consumers; they also were able to use batteries, which resulted in greater reliability and more economical methods of handling peak loads. Although the d.c. system appeared at first to have advantages, the increasing loads resulting from the commercial development of the induction motor and the greater distances over which distribution was required eventually favoured the a.c. system, with its possibility of higher voltages and greater economy; by about 1900, therefore, the battle of the systems in the field of distribution was virtually over, with alternating current the undoubted victor.

The earliest electric traction schemes used direct current, but in 1904 there was built, in Switzerland, the first single-phase locomotive operating from a contact wire fed with alternating current. With d.c. traction schemes the contact-wire voltage is limited to 1·5 or 3kV, so that, although the locomotives are simple and inexpensive, the large currents require a heavy contact-wire system with convertor substations every 5 or 6 miles. The a.c. system employs a transformer on the locomotive, so that the contact-wire voltage can be 15 or 20kV, with, consequently, a much lighter contact-wire structure and substations at intervals of 20 or 30 miles; the locomotives are, however, heavier and more complicated. Motor-design limitations, telephone-interference problems and voltage-drop difficulties with the a.c. system have hitherto necessitated the use of a low frequency ($16\frac{2}{3}$ or 25c/s), so that either a separate railway power supply network or expensive frequency-changer substations to convert from the industrial frequency have had to be employed. Nevertheless, up to the beginning of the recent war the track mileage of railways electrified on the a.c. and d.c. systems has always been about the same. Recent developments in motor-generator sets and mercury-arc rectifiers enabling them to be mounted on a locomotive, and the development of the single-phase series motor for 50c/s operation, have permitted the building of satisfactory locomotives taking a 50c/s supply from a high-voltage contact wire. This has given a decided stimulus to the advocates of a.c. traction, and the recent 50c/s electrification schemes of the French National Railways, the Belgian Congo Railway and, on a smaller scale, the Lancaster–Heysham section of British Railways are being watched with interest. The battle of the systems on the field of electric railway traction is thus just at its height.

In the field of long-distance transmission the simple three-phase a.c. system was practically unchallenged up to the beginning of the recent war. Attempts to use the Thury constant-current d.c. system met with some success, and the development of the grid-controlled mercury-arc rectifier led to some experimental d.c. transmission schemes just before and during the war; for the transmission distances then envisaged such schemes could not, however, compete technically or economically with a.c. transmission. The limiting distance for simple a.c. transmission is 250–300 miles with overhead lines and 30–40 miles with cables, and after the war a number of schemes for distances considerably greater than these were contemplated. To employ alternating current for such distances necessitates costly line-compensation methods and extra-high-speed circuit-breaking devices, whereas with direct current distance introduces no problems; various authorities quote 300–400 miles as the distance beyond which direct current might be expected to be more economic for an overhead-line scheme; for a cable scheme the distance is 30 to 40 miles. The problem facing Swedish engineers of transmitting power over the 62 miles from the mainland to the island of Gotland could therefore only be solved by the use of direct current; a 20MW 100kV d.c. line (with the sea as one conductor) was therefore put into service in March, 1954. This is the first commercial d.c. transmission scheme using mercury-arc convertors, and its inauguration is an event in the pageant of engineering history comparable in significance with that of Ferranti's single-phase 10kV installation between Deptford and the West End of London in 1891. On the last occasion on which Lord Kelvin spoke at The Institution (7th March, 1907) he said, "I have never swerved from the opinion that the right system for long-distance transmission is the d.c. system." It may well be that he was, after all, quite right, as the battle of the systems in the field of long-distance transmission seems to be just commencing.

Mr. Taylor is at the Heriot-Watt College, Edinburgh.

Abstract No. 18
Feb. 19

SOUTH-WEST SCOTLAND SUB-CENTRE: CHAIRMAN'S ADDRESS

By R. J. RENNIE, B.Sc., Member.

"THE PERFORMANCE OF DISTRIBUTION EQUIPMENT IN SERVICE"

(ABSTRACT *of Address delivered at* GLASGOW, *6th October*, 1954.)

The paper presents a review of the performance of distribution equipment in service on the South West Scotland Electricity Board system over the six-year period from April, 1948, to March, 1954. The area covers 5 000 square miles, serving over 770 000 consumers with a simultaneous maximum demand of 810 MW. Supplies are taken from the 132 kV Grid at 22 points. No reference is made to the small and rapidly diminishing 3·3 kV, 2 kV and d.c. networks. The average number of faults recorded annually was 1 764, of which 53% occurred on overhead lines and 32% on underground cables.

The average number of faults on transformers per 100 per annum was 0·6, of which nearly half were due to lightning. During the six-year period the number of transformers in service has increased from 5 425 to 8 340, and as these are mainly pole mounted, the liability to voltage surges due to lightning has increased. A large number of transformers are still in service after more than 30 years' continuous use.

In considering h.v. switchgear, it is shown that, with more than 10 000 circuit-breakers in service, the average number of faults per annum was 25, 6 being due to lightning, 6 to insulation failure, 4 to operational errors and 9 to other causes. Despite the rapid increase in prospective fault currents consequent upon network expansion in recent years, so that most h.v. switchgear installed more than 25 years ago must be considered as obsolete, only one circuit-breaker failure due to inadequate rupturing capacity has been recorded.

Faults in protective gear have averaged 55 per annum, of which 19 were due to faulty discrimination on one extensive network having over-current relays and current-transformer-operated trip coils in series, a condition which is being improved by 33 kV reinforcement. Incorrect functioning of protective gear occurred in 7·9% of all oil-circuit-breaker operations in the clearance of faults on h.v. networks.

There are 2 747 miles of h.v. cable in service, of which 93% are included in the voltage range 25–6·6 kV reviewed in the paper. The average numbers of faults per 100 miles per annum were: 6·6 kV, 1·12; 11 kV, 8·04; 25/20 kV, 3·09. The primary causes were fairly evenly divided between failures of cable insulation, joints and cable end-boxes, with lightning, ground subsidence, and electrolysis as secondary causes. Sections of the 6·6 kV cable network have now been in service for 50 years, and a fair proportion of the cable networks operating at 25–6·6 kV have been live for 30 years. The fault incidence on these old cables during the last 6 years has been generally better than that of cables laid during the last 15 years. It is therefore not yet possible to predict the economic life of h.v. underground cables. The total length of l.v. distributors and services now amounts to slightly over 6 000 miles; the average number of faults per annum per 100 miles was 7·1.

It is generally recognized that h.v. overhead lines form the most troublesome and least reliable part of a distribution system; those in this Area have accounted for 69% of all h. faults recorded. These faults are usually easily repaired, an the economic advantage of overhead lines compared with unde ground cable is such that their use is rapidly expanding. O of a total of 3 303 miles of h.v. overhead lines, 88% operate 11 kV and accounted for 93% of all overhead line faults. Th average number of faults per annum per 100 miles of line wa 26·5, of which 13·3 were due to lightning, no cause could b found for 3·7, 2·7 were due to gales and snow, 2·4 were du to birds and 1·5 to objects fouling the lines. The remainin 2·9 were divided among 6 minor causes. Approximately 95 of lightning faults are transient but still troublesome; in on lightning storm in May, 1953, 303 interruptions were caused b blown fuses. Efforts are being made to mitigate this by omittin fuses on transformers connected to spur lines and by the use auto-reclosing circuit-breakers and surge absorbers at certai points on the system. The whole problem of outages due t lightning is being studied in collaboration with the Electric Research Association. The use of unearthed construction being extended in an effort to reduce the number of faults du to birds. The rate of replacement of wood poles due to deca is about 0·16 per 100 per annum, but as this rate will probabl increase in future, 15 000 poles have been treated by injectio of soluble preservative in order to test the effectiveness of th method of extending pole life. The results to date appea promising.

L.V. overhead lines and services, of which 1 844 miles hav been erected, show an average fault incidence of only 12·9 p 100 miles per annum. These lines are unaffected by lightnin birds or light wind-borne material.

A comparison between the cost of repairs and the total revenu expenditure on distribution provides a fair measure of th relative importance of faults in the maintenance of public ele tricity supply. The annual expenditure on faults was fairl constant at 9·3% of the total revenue expenditure on distrib tion. Although h.v. overhead-line faults accounted for 69 of all h.v. faults, the expenditure on them was only 14·5% the total.

Uninterrupted supply is the aim of every distribution e gineer, and therefore the importance of any fault should b measured in terms of the extent of any interruptions of suppli which may result. Thus the consumer-hours of interruptio are estimated for every fault. The average consumer-hours lo owing to faults, expressed as a percentage of the maximu available consumer-hours, amounted to 0·0086. The record continuity of supplies must have been considerably better tha this figure in the urban areas and somewhat worse in the rur areas.

The sole justification for the compilation of fault statistics to provide information which may lead to improvements technique. In order to evaluate correctly the result of a change in practice, a number of years must necessarily elaps during which accurate fault recording would be essential.

Mr. Rennie is with the South West Scotland Electricity Board.

Abstract No. 1827
Feb. 1955

TEES-SIDE SUB-CENTRE: CHAIRMAN'S ADDRESS

By E. J. GRUBB, B.Sc., Member.

"THE HISTORY AND DEVELOPMENT OF THE ELECTRIC SUPPLY INDUSTRY ON TEES-SIDE"

(ABSTRACT *of Address delivered at* MIDDLESBROUGH, 6*th October*, 1954.)

The Address covers the history of the supply industry on Tees-ide, starting with a brief description of Tees-side before the nvention of the incandescent carbon-filament lamp, and then racing its development.

In 1890, provisional lighting orders were taken out by Stockton nd Darlington Corporations, followed later by West Hartlepool nd Middlesbrough. The first public supplies were given at altburn in 1899 by the Cleveland Trust Co., a non-statutory ompany which laid its cables in the streets under wayleave greements.

Middlesbrough Corporation started the first steam power tation in 1900, followed by Darlington, West Hartlepool and tockton, which all used d.c. 3-wire networks. In 1901, the Cleveland and Durham Counties Co. was granted power rights n a considerable area; this company developed initially in the Bishop Auckland area with a 2·2kV 3-phase system, but in 906 it opened Grangetown power station at which, for the first ime, the alternators generated directly at 11 000 volts, a voltage ince universally adopted. The 11kV system from this station rew rapidly, and supplies were given to various iron and steel vorks, ironstone mines and chemical works, and by 1909 a umber of waste-heat stations were connected to the system. These stations used exhaust steam from the blast engines and urbo-blowers in the ironworks, and in that year interconnection vas made by means of a 20kV cable with the companies which vere operating on Tyneside; thus, for the first time, power tations 40 miles apart were run in parallel. The main purpose f this connection was to enable the surplus power from the vaste-heat stations to be transmitted to the Tyne, but it soon ecame a main source of supply to Tees-side.

Following this, bulk supplies were given by the Power Com-any to Middlesbrough and Stockton Corporation under-akings, and in 1914 to the North Eastern Railway Co. at two oints for the electrification of the Newport and Shildon railway, t each of which there were pairs of rotary convertors connected n series to give 1 500 volts d.c.; this is thought to be the first lectric mineral line in the country, but it was subsequently losed down owing to lack of traffic.

Mr. Grubb is with the North Eastern Electricity Board (Tees Sub-Area).

High-voltage distribution was meanwhile started in Darlington and West Hartlepool from their own power stations at 6kV, and in Middlesbrough and Stockton at 11kV from bulk-supply points. In addition, Skelton and Brotton, Eston, Redcar and Guisborough local authorities also started undertakings, taking bulk supplies. The increased loads on the Cleveland and Durham Company's own system, as well as these bulk supplies, were met by a new power station at North Tees (commissioned in 1921), from which power was taken to the south of the river by cables laid in two trenches dredged in the river bed. Connection to Tyneside at 66kV was completed in 1926.

In that year, an Act of Parliament created the Central Electricity Board and controlled power station development, and this, coupled with standardization of frequency in the 1930's, caused the closing of most of the smaller power stations.

The experience gained in the North-East of operating a highly interconnected network was used by the C.E.B. in interconnecting all the major undertakings in the country, and by 1939 the whole country was operating in parallel.

Rural electrification on Tees-side was almost exclusively provided by the Cleveland and Durham Co., which in 1932 was finally absorbed with the other private companies in the North Eastern Electric Supply Co.

Progress was rapid and continuous until the Second World War restricted capital expenditure to war-time supplies, the extension of North Tees power station and the building of a new power station at Darlington.

Nationalization has now combined all the supply undertakings on Tees-side, generation and transmission coming under the North Eastern Division of the British Electricity Authority and distribution under the Tees Sub-Area of the North Eastern Electricity Board.

Since vesting day, the major event on Tees-side has been the building of a new power station—North Tees "C."

[A series of lantern slides illustrated the changes that have taken place in the industry over the years, and the speaker concluded by observing that discoveries, especially in the atomic field, were so rapid that it was impossible to predict development in the next half-century.]

Abstract No. 182
Feb. 195

WEST WALES SUB-CENTRE: CHAIRMAN'S ADDRESS

By G. D. CURTIS, B.Sc., Member.

"THE ELECTRICAL HAZARD IN EXPLOSIVE ATMOSPHERES"

(ABSTRACT *of Address delivered at* SWANSEA, 14*th October*, 1954.)

Flameproof Equipment.—The introduction of electricity to the mines in the latter part of the 19th century led to an awakening of interest in the possibilities of the ignition of fire damp by electrical apparatus. By about 1905, a "gas proof" enclosure had been evolved, but it was found impossible to maintain such types of equipment gas proof and gas tight, and in 1908 an "explosion proof" enclosure, calculated to withstand an internal pressure of 200lb/in^2, was proposed. Immediately prior to the First World War the broad-flanged type of casing joint was developed and the term "flame-proof" was used to define this construction.

To ensure that such apparatus was indeed flameproof, some of the manufacturers installed their own testing equipment. There was, however, an obvious need for an independent authority which could establish the safety of equipment by a standard procedure, the onus for design acceptability, or otherwise, being left to be settled between the manufacturer and purchaser. Eventually, in 1921, the Mines Department issued a recommendation that purchasers should obtain a guarantee from the manufacturers that apparatus for use in gassy mines was certified as flameproof. In consequence of this recommendation and requests from various sources, Sheffield University, in collaboration with the Safety in Mines Research Board, agreed to conduct research work, and in 1922 the University undertook to conduct tests and, if satisfied, to issue Flameproof Certificates. The University also published some general instructions to manufacturers in which were included requirements for the design of flameproof enclosures. In general, these requirements were embodied in the 1940 revision of B.S. 229.

The need for flameproof equipment for industries other than coal mining led to tests at Sheffield University using pentane and acetone vapours, and gases other than methane, or fire damp, had been mentioned in the 1929 revision of B.S. 229.

By 1931 the Department of Mines had set up its own Testing Station at Buxton. Up to about 1930, oil-immersed equipment had been regarded as essentially safe. Experiments showed, however, that during the passage of an arc through hydro-carbon oils a mixture of hydrogen, acetylene and other gases was given off, and for these the requirements were considerably more stringent than for gases hitherto specified. These requirements were included in the 1940 revision of B.S. 229.

In 1936 the Factory Department became interested in the possibility of the ignition of inflammable gases other than fire damp, pentane and acetone vapours. The Safety in Mines Research Board therefore agreed to undertake research on flame ignition and propagation for additional gases. The Electrical Research Association drew up a programme for this work and agreed to finance it.

It was natural at this time that some form of group classification for gases should be made, and in a Mines Department Circular issued in 1936, three groups were mentioned: Group 1, methane and fire damp; Group 2, pentane vapours; Group 3, coal and coke gases. This classification in an extended form is used to-day.

The 1940 revision of B.S. 229 included a comprehensive section on the design and construction of flameproof enclosures an gave diagrams of several typical methods of complying with th various design requirements. The latest revision, that of 194(has an additional section on the grouping of gases and ga dimensions.

The safety afforded by the use of flameproof equipment i conditional and not absolute. It is of the utmost importanc that possible overloads and short-circuits should be within th rating of the equipment, an essential consideration in this cor nection being the possibility of damage to enclosures by allowin short-circuits to persist for relatively long periods.

The maximum short-circuit breaking capacities for flameproc equipment are generally 25 MVA for 3 300 volts and 5 MVA fo 440 volts.

Intrinsically Safe Electrical Equipment.—Following an ex plosion at Senghenydd in 1913, tests were conducted to establis conditions in which the sparking produced by d.c. signallin bells could initiate combustion of a methane-air mixture up to this time such sparking not having been considere dangerous. Tests established that the safe or dangerous natur of such sparking in given circumstances depends upon th duration and energy of the sparks, but no empirical formul holding for all conditions was found. Those d.c. bells failing t initiate combustion under any conditions were classed a intrinsically safe. A great deal of research has since bee conducted into the ignition of inflammable atmospheres by weal sparks, and although some general principles have been laic down, the only means of establishing safety, or otherwise, of suc equipment is by exhaustive tests. Such tests are undertaken b the Ministry of Fuel and Power, which issues certificates o intrinsic safety for apparatus for use in the mining industry.

Subsequently, the application of intrinsic safety was extende from d.c. signalling equipment to cover magneto telephones, a.c bells and charge exploders. More recently, certificates have bee granted for electrical equipment for the automatic control o processes, with particular application to the oil industry.

Approved Apparatus.—In certain circumstances, the use o electrical equipment which meets neither flameproof require ments nor those of intrinsic safety is permissible. Typica apparatus falling into this class are certain types of battery operated hand-lamps and torches. The Ministry of Fuel an Power and the Home Office are empowered to give writte approval for the use of specially designed equipment in specifie atmospheres.

Ignition by Static.—In addition to apparatus for use in powe and light-current circuits using conductors, a further source c danger must be mentioned, namely that from static electricity This is disposed of by effective earthing which may be applie by direct methods or by the use of radioactive materials whic ionize atmospheres. Static in its most dangerous form occur when charges are allowed to build up on unearthed conductin objects. In most cases, very low earth resistances are nc necessary to prevent static build-up, since the rate of charg is small; paint films, however, can have high resistance, an earthing must be deliberate and not fortuitous.

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Feb. 1955

THE EFFECTS OF PRE-LOADING ON FUSE PERFORMANCE

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SUMMARY

In actual operation, when a fault occurs on a fused circuit, this rcuit will probably be carrying a load current, so that the fuse element ill be at some temperature above ambient, and this will affect its perating characteristics under the fault conditions. Standard specifitions of test do not take this into account, so that fuses are tested hen initially at ambient temperature.

Tests carried out on fuses with single-wire elements over a wide nge of load and fault currents are described. These have shown e range and amount of the reduction in pre-arcing time caused by preading; allowances for this reduction suggested previously do not pear to have been complete. The arcing time is also affected, and e transient voltage produced by the fuse when interrupting the circuit reduced by pre-loading.

Tests at a constant prospective current, with the instant of circuit osure varied throughout a half-cycle, have shown large variations in e-arcing times and in transient voltages, both for pre-loaded and nloaded fuses.

The temperature rise of the element centre for any load current has een calculated and verified by tests using temperature-sensitive paints. /ith a knowledge of this temperature, the reduction in the currenteat integral with pre-loading has been calculated and checked sperimentally.

(1) INTRODUCTION

When a fault occurs on a fused circuit it will generally be hen the circuit is complete and carrying a load current. The mperature of the fuse element will therefore be above ambient, nd this will reduce the pre-arcing time, and may affect other perating characteristics. There are a large number of pre-load onditions which may occur during fuse operation, and this has ot been taken into account in the standard specifications of st of any country. These specifications (e.g. B.S. 88: 1947) call r the fuse to be initially at an ambient temperature of about)°C. Time/current characteristics, which are determined on st or calculated, will therefore give times which are upper-limit alues.

This effect of pre-loading in reducing the pre-arcing time is of articular interest where close discrimination between fuses, or etween fuses and circuit-breakers, is required. Lincks[1] states at a fairly large fusing ratio is necessary between fuses conected in series for sectionalizing, as is common in rural disibution systems, even where they have the same operating naracteristics. This is necessary to allow for normal operating nd manufacturing variables, the greatest of which is the differnce in the normal load carried by the two fuses. He therefore iggests that all published time/current characteristics should ate the initial temperature of the fuse element when tested.

According to Lincks, the total interrupting time for a fuse perating at the temperature resulting from full rated current ill be from 35 to 50% less than that when starting at normal ambient temperature, and the degree of this variation is dependent upon the fault current, because this affects the relative proportions of the heating and arcing periods.

A correction factor was given by Williams[2] to be applied to the time given in normal time/current characteristics. Two curves given by him show the variation of this factor with load current—one curve for fuses below 3 amp rating and the other for those above 5 amp rating—but no mention is made of the variation of the factor with fault current, and it was stated that pre-loading had no appreciable effect upon the arcing time curve.

In a paper on the co-ordination of fuses and oil circuit reclosers by Auer *et al.*,[3] a 15% reduction in melting time owing to pre-loading and a 10% reduction owing to the progressive melting of the fusible element and strain wire were suggested.

In the discussions on Reference 3, the view was expressed that the heating and cooling of fuses has been one of the larger intangible problems in distribution co-ordination in recent years. Its importance lies in the benefits of selective operation between circuit-breakers or reclosers and fuses, namely improved service continuity and reduced operating cost.

This paper describes an investigation made with one fuse, to determine how the reduction in pre-arcing time is affected by the fault and load currents, and to observe any other effects of pre-loading.

(2) APPARATUS FOR TESTS

Since most fuses are installed on a.c. systems and there are no satisfactory substitute d.c. tests for a.c. operation, the tests were carried out on an a.c. circuit.

In order to make comparative tests, it is necessary to be able to control the point of the cycle at which the circuit is closed.

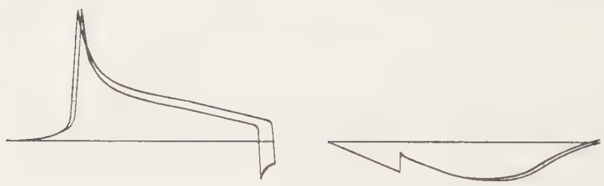
(2.1) Timing Circuit

To control the point of cycle, a circuit developed by the E.R.A.[4] was used. A pilot alternator geared to the main machine supplies a 3-phase transformer with tapped secondary winding connected to selector switches. A voltage of constant amplitude but variable phase can thus be applied to a peaking transformer, which triggers a thyratron in the operating-coil circuit of a single-phase making switch.

By reducing friction in the switch, a minimum make-switch time (i.e. between the start of current in the operating coil and contact closure) of 0·069 sec was obtained. Owing to friction the minimum standard deviation in the point on the voltage wave at which the circuit made was 4·5°.

The superimposed oscillograms of fuse current and transient voltage for two successive tests, shown in Fig. 1, illustrate the high degree of consistency obtained. These oscillograms were obtained from a three-tube cathode-ray oscillograph with single-stroke time-base triggered from the signal through a 1 microsec delay cable, while the actual signal was applied to the deflection plates through a 2 microsec delay cable.[6] Throughout most of the tests described in this paper, both Duddell and cathode-ray oscillographs were used simultaneously.

Written contributions on papers published without being read at meetings are vited for consideration with a view to publication.
Dr. Guile is in the Electrical Engineering Department, Queen Mary College, niversity of London.
The subject-matter of the paper forms part of a thesis presented for the degree of octor of Philosophy at London University.



(a) (b)

Fig. 1.—Oscillograms of two successive tests, superimposed to illustrate consistency of instant of closing circuit.

(a) Voltage across fuse. (b) Current through fuse.

(2.2) Load-Current Switching

A number of fuses were connected in series and carried load current until a steady temperature was reached. They were then transferred, one by one, to the test circuit, where they were connected to a further loading circuit for a few minutes to recover a steady temperature until fault current was applied. This method avoided the need for large variable impedances and gave a rate of testing which was almost as high as that for unloaded fuses.

There was found to be a minimum time delay of 0·073 sec, with standard deviation of 0·0049 sec, between load current ceasing and fault current commencing. This delay, being largely determined by the make-switch closing time of 0·069 sec, could not be reduced with the make switch available.

In order to find what time lag between these currents could be tolerated without appreciable cooling of the fuse element, an element of No. 29 S.W.G. copper in a porcelain cartridge filled with quartz powder was heated by 90% minimum fusing current, i.e. 16 amp. This current was suddenly reduced to 1 amp, and the element current and voltage were then recorded on a Duddell oscillograph. The element resistance, R_θ, as a ratio of its value at ambient temperature, R_{20}, is plotted in Fig. 2.

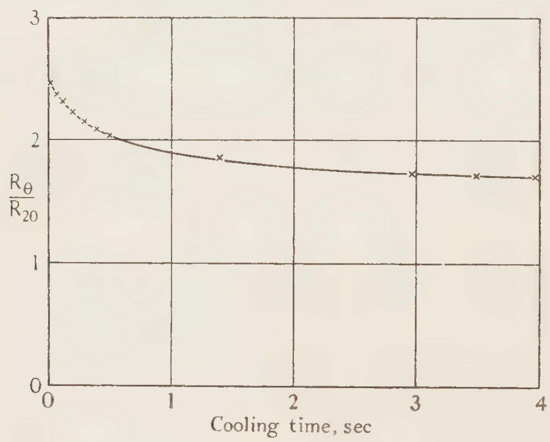


Fig. 2.—Cooling of No. 29 S.W.G. element.

R_θ = Resistance of half-element at any temperature θ.
R_{20} = Resistance of half-element at 20° C.

The fall in resistance of the No. 29 S.W.G. element during this time of 0·073 sec, when the fuse is carrying no current, can be seen from Fig. 2 to be only 6%. In Section 10.1 it is shown that this corresponds to a fall in temperature at the centre of the element of only about 4% of the melting temperature.

(3) TESTS ON PRE-LOADED FUSES AT CONSTANT PROSPECTIVE CURRENT AND VARIED CURRENT ASYMMETRY

The fuse tested under pre-load conditions was a No. 34 S.W.G. copper element lying centrally in a porcelain cartridge, 3·5 cm in internal diameter and 14 cm long, with a quartz filler of densit 1·62 and sieve analysis as shown in Table 1.

Table 1

Quartz-Powder Sieve Analysis

Weight	Grain size
%	
20	− 36 + 60
57	− 60 + 90
20	− 90 + 100
3	−100 + 150

The mimimum fusing current was 11·1 amp, so that the rate current would be about 7 amp. Tests were made with the fus pre-loaded at 3·5, 5·5, 7·5 and 10 amp.

For a given prospective current measured in amperes (r.m.s of the alternating component, the heating effect of the curren depends on the point of the voltage wave at which the curren commences, since this determines the d.c. component of th current. This latter component dies away with the time constant of the test circuit, which in the present case was abou 0·1 sec. For times of this order, therefore, the time/curren characteristic in which prospective current is plotted will var with the point on the cycle at which the circuit closes.

The fuse described was tested at a constant prospective curren which gave total operating times in this range, while the setting of the timing circuit were adjusted to cover 180°.

Fig. 3 shows that the unloaded fuse subjected to this sam

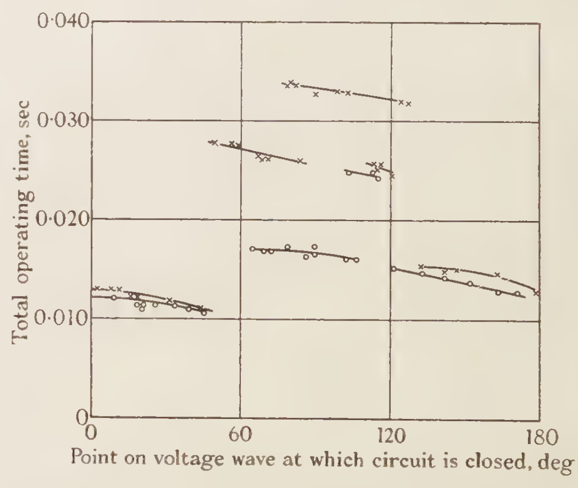
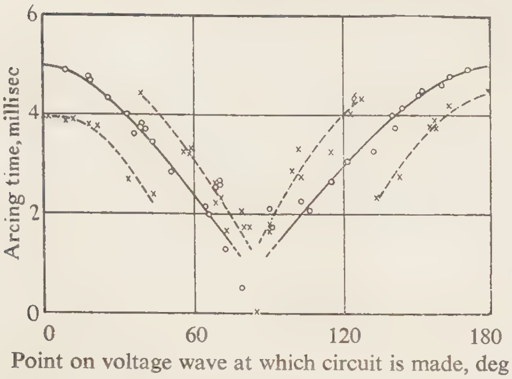


Fig. 3.—Variation of total operating time with the instant of circui closure for a constant prospective current [100 amp (r.m.s.) i first cycle].

× × × Unloaded fuse.
○ ○ ○ Fuse pre-loaded at 90% minimum fusing current.

current clears the fault after one half-cycle if the current com mences between 0° and 45°, after two half-cycles from 45° to 80° after three half-cycles from 80° to 110°, and so on. The operatin time falls slightly as the angle increases from 0° to 45° owing t the decreasing width of the first lobe of current. The tota operating time for this one value of prospective current varie over a range 3 : 1, depending on the instant of initiation. Th pre-loaded fuse behaves in a similar way, but the times and thei range of variation are smaller.

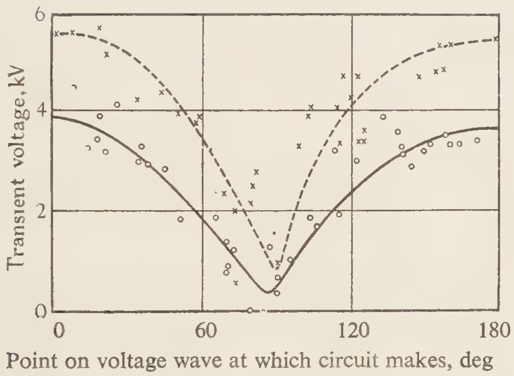
Fig. 4 shows that the arcing time varies very considerabl with the point on the cycle. The discontinuity at 40° is due t the fact that, as the angle increases, the asymmetry is decrease



g. 4.—Variation of arcing time with the instant of circuit closure for a constant prospective current [100 amp (r.m.s.) in first cycle].

× × × Unloaded fuse.
○○○ Fuse pre-loaded at 90% minimum fusing current.

the point where the fuse cannot clear in one current loop. here is scatter at about 80° or 90°, since the current at the start

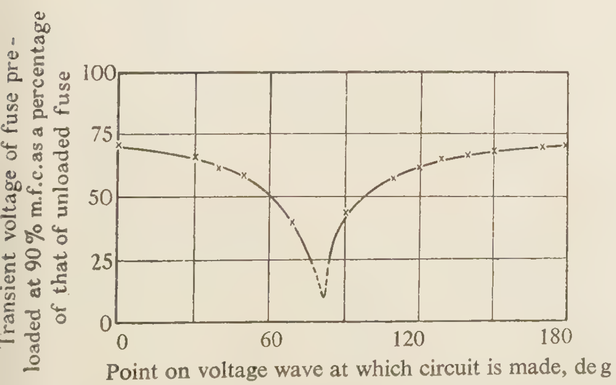


g. 5.—Variation of transient voltage with the instant of circuit closure for a constant prospective current [100 amp (r.m.s.) in first cycle].

× × × Unloaded fuse.
○○○ Fuse pre-loaded at 90% minimum fusing current.

arcing for this condition is very low. The pinch effect is en very small and may be insufficient to cause melting of the ement from the outside surface inwards to the axis, so that eak-up becomes irregular and there is little or no multiple cing.

This scatter at that point is shown similarly in the transient ltage, as can be seen from Fig. 5. This Figure shows that the ansient voltage produced by the fuse in a circuit of 1 500 volts



. 6.—Comparison of transient voltages of loaded and unloaded fuses with variation of instant of circuit closure, for a constant prospective current [100 amp (r.m.s.) first cycle].

varied between 5 500 volts and zero according to the point on the cycle. It has been observed by Baxter[8] that the transient voltage depends upon the current at the start of arcing, and since the latter varies with the point on the cycle, this explains the variation in Fig. 5. It is not necessarily true that every fuse produces maximum transient voltage when the circuit is made at voltage zero; it depends on the size of the element, and at what point on the current wave sufficient energy to disrupt the element has been supplied. Fig. 5 shows that the transient voltage of the fuse loaded at 90% minimum fusing current is similar in its variation but lower in value, and it can be seen from Fig. 6 that it does not exceed 70% of that for the unloaded fuse.

(4) TESTS ON PRE-LOADED FUSES OVER A RANGE OF FAULT CURRENTS WITH CONSTANT-CURRENT ASYMMETRY

(4.1) Fuses with Single Axial Element

It can be seen from the results of the previous Section that a time/prospective-current characteristic can only be drawn for a given instant of circuit closure.

In these tests, the fuse previously described was tested over a range of fault current with the circuit closed at 55° ± 5°. This is a point where the variation of heating with a small change of angle will not be too great.

Since banks of variable reactors and resistors had not at that time been completed, the current had to be controlled by keeping the circuit connections unchanged and varying the alternator excitation.

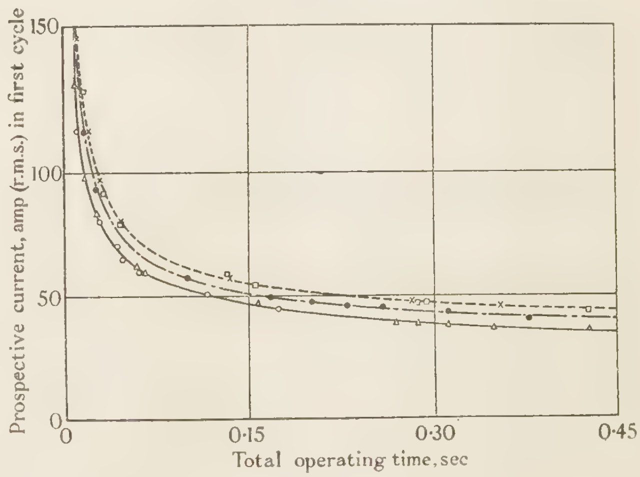


Fig. 7.—The effect of pre-loading on a time/current characteristic.

× × × Unloaded fuse.
● ● ● Fuse pre-loaded at 67% minimum fusing current.
△△△ Fuse pre-loaded at 90% minimum fusing current.
□□□ Unloaded fuse with helical element.
○○○ Fuse with helical element pre-loaded at 90% minimum fusing current.

Fig. 7 shows that test results taken between 50° and 60° are extremely consistent for loaded and unloaded fuses. Fig. 8 shows how the total operating time for any particular load and fault may be determined, the variation in time becoming less as the fault current is increased.

It can be seen from Fig. 9 how both total operating and pre-arcing times for unloaded and pre-loaded fuses compare with variation of fault current. The two times follow the same pattern over the whole range, but at very low fault currents the percentage pre-arcing time exceeds the percentage total operating time, and at higher fault currents this condition is reversed. This is due to the arcing time of the unloaded fuse being con-

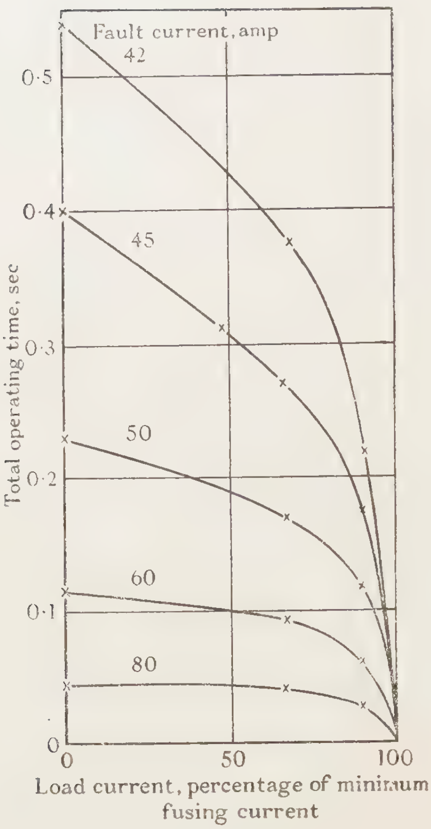


Fig. 8.—The effect of pre-loading on total operating time, for No. 34 S.W.G. copper.

siderably greater than that of the pre-loaded fuse at low fault currents, as shown by Fig. 10. At high fault currents the arcing time is increased by pre-loading. The arcing-time characteristics of Fig. 10 are similar to those shown by Williams,[2] except for a rise in arcing time which occurs at higher fault currents. This is probably due to the increased circuit voltage, which reaches 3kV at a fault current of 200amp.

This is some scatter in Fig. 10 owing to the large variation of arcing time with angle shown in Fig. 4, so that a comparison has been made in Table 2 between fuses which have been tested at or very near the same point on the cycle, and this confirms Fig. 10.

There is a discontinuity in Fig. 9 for a fuse loaded at 90% of

Table 2

THE EFFECT OF PRE-LOADING ON ARCING TIME

R.M.S. current in first cycle	Point on voltage cycle at which circuit is made		Arcing time		Arcing time pre-loaded as a percentage of unloaded time
	Unloaded	Pre-loaded 90% minimum fusing current	Unloaded	Pre-loaded	
amp	deg	deg	sec	sec	%
47·5	60	53	0·020	0·006	30
98	58	62	0·0038	0·0034	90
117	76	76	0·0016	0·0019	119
137	56	54	0·0035	0·0042	120
155	60	60	0·00385	0·00435	113
165	47	44	0·00485	0·0053	109

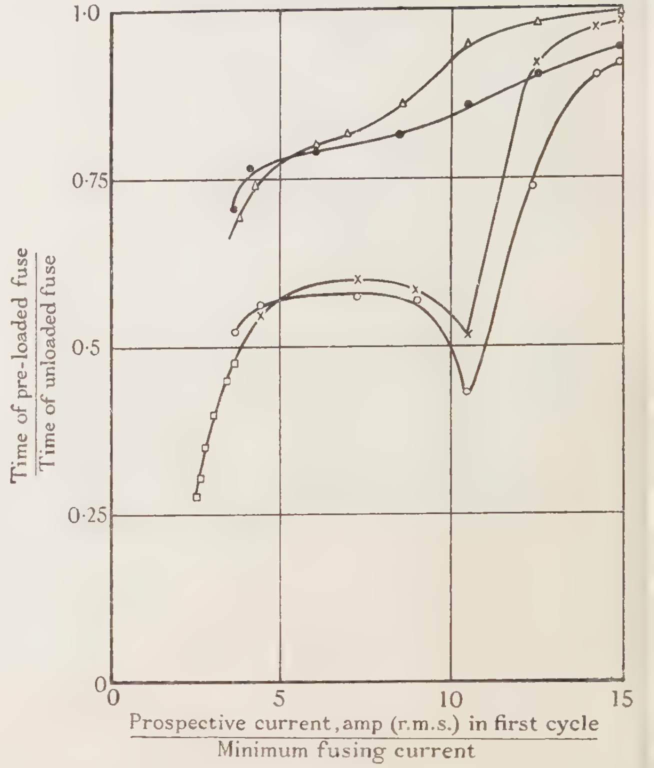


Fig. 9.—The effect of pre-loading on total operating and pre-arci[ng] times.

△ △ △ Total operating time of fuse pre-loaded at 67% minimum fusing current.
● ● ● Pre-arcing time of fuse pre-loaded at 67% minimum fusing current.
× × × Total operating time of fuse pre-loaded at 90% minimum fusing current.
○ ○ ○ Pre-arcing time of fuse pre-loaded at 90% minimum fusing current.
□ □ □ Pre-arcing time of fuse pre-loaded at 90% minimum fusing current (lo[w] current tests).

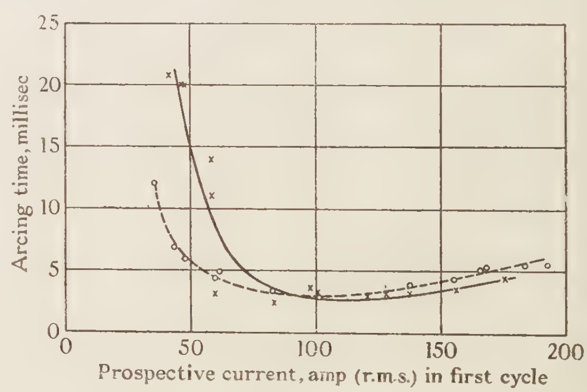


Fig. 10.—The effect of pre-loading on arcing time.

——× × × Unloaded fuse.
- - -○ ○ ○ Fuse pre-loaded at 90% minimum fusing current.

the minimum fusing current. This is due to the fact that t[he] pre-loaded fuse interrupts this fault in one current loop, while t[he] unloaded fuse carries current for two loops. At slightly low[er] fault currents the times are two and three loops respectively, [so] that the ratio rises again before falling away at very low fa[ult] currents.

The pre-arcing time of the pre-loaded fuse has become [an] almost constant fraction of that for an unloaded fuse at fa[ult] currents greater than about 15 times the minimum fusing curre[nt]. Tests made at a prospective current of 1 000amp, on the sa[me]

Table 3

THE EFFECT OF PRE-LOADING ON THE CURRENT AT THE START OF ARCING

R.M.S. current in first cycle	Point on voltage cycle at which circuit is made		Transient voltage		Transient voltage pre-loaded as a percentage of that unloaded	Current at start of arcing	
	Unloaded	Pre-loaded 90% minimum fusing current	Unloaded	Pre-loaded		Unloaded	Pre-loaded
amp	deg	deg	volts	volts	%	amp	amp
98	66	66	2 100	1 000	48	97	119
117	76	76	2 375	1 580	66·5	145	132
137	56	54	3 870	3 220	83·2	265	275
155	60	60	4 200	3 500	83·3	305	285

ise pre-loaded at 67% minimum fusing current, showed the re-arcing time to be about 3% less and the arcing time 3% more ian for an unloaded fuse, so that there was no appreciable ifference in total operating time.

Fig. 11 confirms the dependence of transient voltage on current the start of arcing, as observed by Baxter.[8] It appears from ig. 12 that the transient voltage of a pre-loaded fuse does not each that of an unloaded fuse for a given current at the start of rcing, even for very high fault currents. The loading of the fuse causes the current at the start of arcing to be altered slightly, as shown in Table 3.

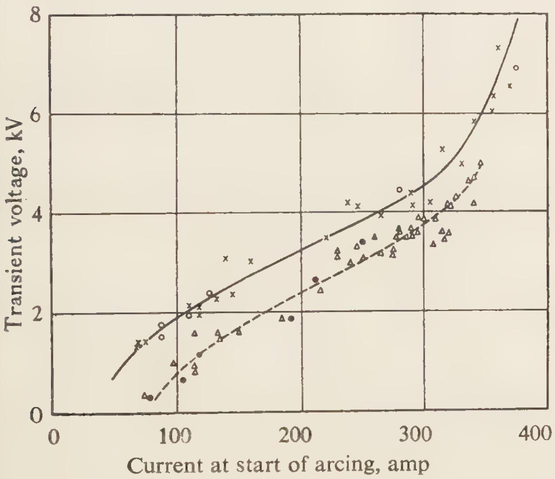
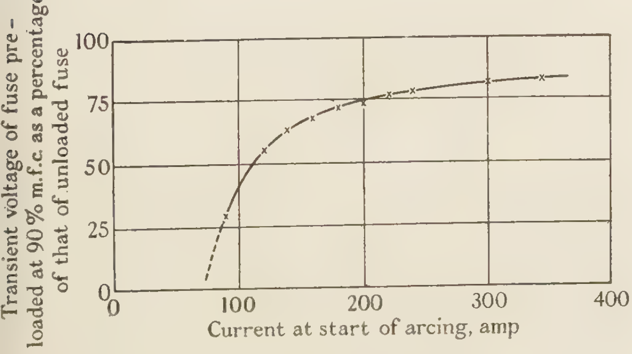


Fig. 11.—The effect of pre-loading on transient voltage.

——× × × Unloaded fuse.
——○ ○ ○ Unloaded fuse with helical element.
- - -△ △ △ Fuse pre-loaded at 90% minimum fusing current.
- - -● ● ● Fuse with helical element pre-loaded at 90% minimum fusing current.



g. 12.—Comparison of the transient voltages of loaded and unloaded fuses with variation of current.

At 98 amp the current at the start of arcing is increased by pre-loading, since at that current the fuses clear in two and three loops, respectively. At higher currents, with one loop only, the current at the start of arcing is slightly reduced by pre-loading. The comparison of individual fuses in Table 3 shows that the small change in current at the start of arcing can be neglected in using Fig. 12 as a direct indication of the reduction in voltage.

As would be expected, the cut-off current is slightly reduced by pre-loading, as shown in Table 4, the corresponding fuses being tested at the same prospective current.

Table 4

THE EFFECT OF PRE-LOADING ON CUT-OFF CURRENT

Point on voltage cycle at which circuit is made		Cut-off current	
Unloaded	Pre-loaded 90% minimum fusing current	Unloaded	Pre-loaded
deg	deg	amp	amp
40	50	285	250
60	60	327	308
50	53	355	327

Low-current tests were carried out against time measured by a relay-operated time-interval meter or a stop watch. In these tests the ratio of prospective current to minimum fusing current is independent of time, whereas in Fig. 9 the prospective current is measured in the first cycle, where a reactance between sub-transient and transient is operative and the current is falling while the fuse melts. The reactance at the instant of line-to-line short circuit, i.e. $X_d'' + X_2'$, is 15 ohms, while after 1 sec it has increased nearly to the steady-state value of $X_{sd} + X_2$, which is 39·5 ohms. For this reason a ratio of the total operating time of the pre-loaded fuse to the total operating time of the unloaded fuse of 0·5 was found to occur at a ratio of the prospective current to the minimum fusing current of 1·8 in the low-current tests, but in Fig. 9 this time ratio of 0·5 occurs at a current ratio of 4. Scaling the low-current test results by this correspondence gives good agreement with the results of Fig. 9 as shown.

(4.2) Fuses with Single Helical Element

Tests were carried out with No. 34 S.W.G. copper wire wound helically on a star-shaped former. The length of the element was made equal to that of the wire lying along the axis, by winding over a slightly reduced distance with pitch of 6 cm. This was done because the transient voltage is proportional to element length.

It can be seen from Figs. 7 and 11 that, over the time range investigated, there is no difference in time/current characteristic between axial and helical wires, and that there is no change of transient voltages for unloaded or pre-loaded fuses of these two types. Minimum fusing current was increased from 11·1 to 11·7amp by winding the element helically, so that the change in time/current characteristic at low currents is not great.

(5) DETERMINATION OF ELEMENT TEMPERATURE UNDER PRE-LOAD

(5.1) By Test

Measurement of the maximum temperature rise in the element for a given pre-load current by the method of attaching tungsten wires at short intervals along the element[8] has certain disadvantages. The average temperature rise of a short length is measured from the rise in resistance, so that the effect of oxidation is not taken into account. Inaccuracies may arise owing to the difficulty in maintaining good contact between tungsten and element at a constant spacing in a powder-filled cartridge.

In view of this, the steady-state maximum temperature on the element was obtained by using pigments which undergo a permanent change in colour at certain temperatures. These pigments when mixed with alcohol form a paint, and colour changes occur within $\pm 5°C$ when the time of heating is 30min. For longer times the variation in temperature is not great.

It was found that painting the wire at a few points along its length did not alter its minimum fusing current.

After sufficient time was allowed for it to reach steady temperature, the wire was removed from the cartridge and examined. The results of these tests are shown in Fig. 14. Each colour change gives a short line in this Figure, since at the lower current the change had not occurred, but at the higher current the colour change was observed.

(5.2) By Calculation

It has been shown by the author[9] that the temperature rise of the element of the fuse described here may be calculated. In the steady state the result reduces to

$$\theta_1 = \frac{I^2\rho_0}{k_2' J A_1 - I^2\rho_0\alpha} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where θ_1 = Maximum temperature rise of the element above ambient temperature.

ρ_0 = Element resistivity at ambient temperature.

ρ = Element resistivity at temperature rise θ_1.

$\rho = \rho_0(1 + \alpha\theta_1)$.

J = Mechanical equivalent of heat.

A_1 = Cross-sectional area of wire.

I = Constant direct current in fuse.

k_2 = Thermal conductivity of filler.

k_2' is related to k_2 by

$$k_2 = \frac{\theta_1 k_2' \log_\varepsilon \dfrac{r}{r_1}}{2(\theta_1 - \theta_r)}$$

θ_r = Temperature rise above ambient at any radius r.

r_1 = Wire radius.

From eqn. (1) the variation of maximum temperature with pre-load can be calculated, and the result is shown in Fig. 13.

It can be seen that when the scale of the abscissa is current expressed as a percentage of the minimum fusing current, the calculated curve practically coincides with the experimental results. For silver wire a curve very similar to that in Fig. 13 can be calculated, since the resistivity and temperature coefficient of resistance are similar to those of copper.

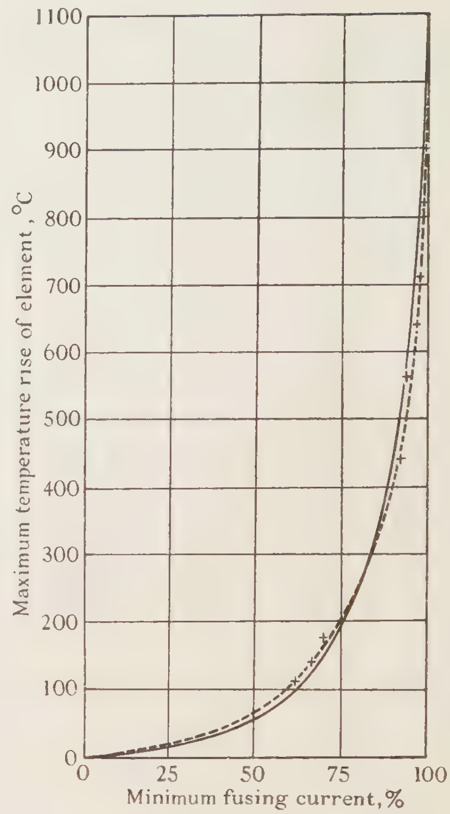


Fig. 13.—Variation of maximum element-temperature rise with loa current for No. 34 S.W.G. copper.

——— Calculated curve.
----- Experimental curve.
+ Experimental result.

(6) THE EFFECT OF PRE-LOADING ON THE CURRENT-HEA INTEGRAL

(6.1) By Calculation

It was shown by Gibson[10] that, in the region where heat lo from the element can be neglected,

$$\frac{i^2\rho_0}{J}(1 + \alpha\theta_1)\frac{dt}{A_1^2} = c_1 d_1 d\theta_1 \quad . \quad . \quad . \quad . \quad ($$

so that for an element heated from an initial temperature equal the ambient,

$$\int_0^t \frac{i^2}{A_1^2}dt = \frac{c_1 d_1 J}{\rho_0\alpha}\log_\varepsilon(1 + \alpha\theta_1) \quad . \quad . \quad . \quad . \quad ($$

where i = Instantaneous fuse current.

c_1 = Specific heat of element.

d_1 = Density of element.

t = Time.

$\int_0^t \frac{i^2}{A_1^2}dt$ was called by Gibson the "current-heat integral

With the case of a constant direct current, I, the integral becom $(I^2/A_1^2)t$. This will vary with the degree of pre-loading, and t variation can be calculated from eqn. (2)

since $$\int_0^t \frac{i^2}{A_1^2}dt = \frac{c_1 d_1 J}{\rho_0}\int_{\theta_p}^{\theta_m} \frac{d\theta_1}{(1 + \alpha\theta_1)} \quad . \quad . \quad . \quad . \quad ($$

where θ_m = Melting temperature rise of element.
θ_p = Maximum element temperature rise due to load current.

Hence
$$\int_0^t \frac{i^2}{A_1^2}dt = \frac{c_1 d_1 J}{\rho_0 \alpha} \log_\varepsilon \left(\frac{1 + \alpha\theta_m}{1 + \alpha\theta_p}\right) \quad . \quad . \quad . \quad (5)$$

From the values of θ_p obtained experimentally and shown in Fig. 13, the variation of the current-heat integral with load current may be calculated, and the results are shown in Fig. 14.

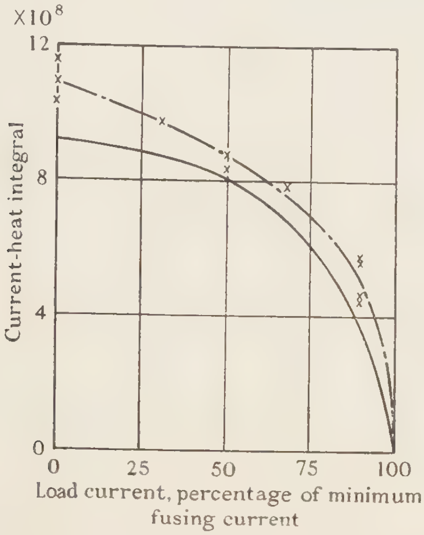


Fig. 14.—The reduction of the current-heat integral by pre-loading.
– – – – Experiment.
——— Calculation.

(6.2) By Test

It has been shown by the author[9] that, for the fuse considered, the heat loss from the element is negligible if

$$I^2 \gg \frac{\pi k_2' J A_1}{\rho_0 \alpha} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

putting

$$I^2 = \frac{10\pi k_2' J A_1}{\rho_0 \alpha} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

gives values of this limiting current which agree very closely with test, where the region of no heat loss is shown by the time/current characteristic plotted on log/log paper, this being linear and of slope −2.

Current-heat integrals for various pre-load currents were computed from oscillograms of tests where the current was considerably greater than that given by eqn. (7), so that there was no loss of heat from the element during the pre-arcing period. These values are plotted in Fig. 14, and lie just above the calculated values over the whole range owing to the time needed for the element to break up into globules.[7]

(7) DISCUSSION OF RESULTS

At prospective currents above about 15 times the minimum fusing current, the change due to pre-loading in total operating time for the fuse tested is very small and can be neglected. At low over-currents, however, the reduction in total operating time is of an order which may need to be taken into account when considering close discrimination. For example, a fuse pre-loaded with its rated current and then subjected to a total fault current of twice the minimum fusing current was found to interrupt the circuit in a time 30% shorter than that when unloaded.

Since the effect of pre-loading on the pre-arcing time of a fuse varies so widely with the magnitude of the fault current, as shown in Fig. 9, the correction factor suggested by Williams[2] should not be applied over the whole range of fault currents. Similarly, the correction factor suggested by Lincks[1] would seem to apply better at low over-currents, and although this factor varies with fault current as suggested by him, the reason he gives, i.e. that the relative proportions of heating and arcing times are affected, is not correct.

The statement of Williams[2] that arcing time is not affected by pre-loading has not been entirely confirmed. There is a tendency for the arcing time to be reduced by pre-loading at low fault currents, but for a slight increase to take place at higher currents.

It was observed that at a particular constant prospective current (about nine times the minimum fusing current), variations of more than 300% in total operating time of an unloaded fuse occurred, when the instant of the cycle at which the circuit closed was varied. The transient voltage under these conditions varied between 5 500 volts and zero.

From Figs. 3 and 4 it can be seen that, while the total operating time varies 300% with the degree of current asymmetry, the change in pre-arcing time is 400%. This large variation in pre-arcing time at a constant prospective current emphasizes the danger in plotting a single characteristic of pre-arcing time against prospective current, as is common. It would seem advisable to plot two limiting curves in the short time region where this variation occurs. It must also be borne in mind, however, that this variation changes with the time-constant of the circuit in which the fuse is used.

It was found that pre-loading at all times reduces the transient voltage produced by a fuse. This is probably due to the temperature distribution at break-up being more peaked than in an unloaded fuse (see Section 10.2).

The maximum temperature rise in a single element of circular cross-section under steady loading has been calculated, and the result agrees with the measured temperatures. The curve of maximum element temperature plotted against percentage minimum fusing current, when compared with that given by Gibson,[10] is found to give considerably lower temperatures throughout the whole range. This indicates a lower temperature for any given fusing factor, i.e. a cooler-running fuse. The differences may in some part be due to the elimination, in the present method of measuring temperature, of some sources of inaccuracy in obtaining a temperature rise by an overall resistance measurement.

Although at high fault currents there is only a small change in total operating time, there is an appreciable reduction in the current-heat integral owing to pre-loading. This is due to the fact that, at these currents, pre-arcing time tends to be reduced somewhat more than total operating time, and the current flowing during the pre-arcing period is slightly reduced. This reduction in current-heat integral has been calculated and verified experimentally.

The fall in overall resistance in Fig. 2 may be shown to represent a fall in temperature at the centre of an element of No. 29 S.W.G. of about 40% in a cooling time of 2 sec. Statements made in the discussion on the paper by Auer *et al.*[3] and endorsed by the authors, to the effect that cooling of an element in this time can be neglected as a factor affecting fusing times in recloser operation, would therefore seem to be applicable only to elements above a certain size.

(8) ACKNOWLEDGMENTS

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The author wishes to acknowledge the advice and encouragement given by Professor W. J. John of Queen Mary College.

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(10) APPENDICES

(10.1) Overall Element Resistance

If R_θ = Resistance of half-element with a particular steady-state temperature distribution.
R_{20} = Resistance of half-element at 20°C.
and l = Length of half element.

then
$$R_{20} = \frac{\rho_0 l(1 + 20\alpha)}{A_1} \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

When the resistance is R_θ, the temperature distribution along the element is of a parabolic form and may be expressed as

$$\theta_1 = B[C(l - z) - D(l - z)^2] \quad . \quad . \quad . \quad . \quad (9)$$

where B, C and D are constants, and z is the axial co-ordinate.

Then
$$R_\theta = \frac{\rho_0}{A_1}\int_0^l \{1 + \alpha B[C(l - z) - D(l - z)^2]\}dz \quad . \quad (10)$$

and hence, for a copper wire, from eqns. (8) and (10),

$$\frac{R_\theta}{R_{20}} = 0\cdot924 + 0\cdot01415BC - 0\cdot066BD \quad . \quad . \quad (11)$$

For a No. 29 S.W.G. copper wire carrying minimum fusing current, the temperature distribution is shown by an electrical analogue of the cartridge fuse[11] to be

$$\theta_1 = 340(l - z) - 27(l - z)^2 \quad . \quad . \quad . \quad . \quad (12)$$

i.e. the constants in eqn. (9) are

$$B = 1,\ C = 340,\ D = 27.$$

This analogue result gives very good agreement with test, since with these values of B, C and D at minimum fusing current, the ratio R_θ/R_{20} is equal to $4\cdot0$.

Tests on this fuse with a current such that the wire fused in four hours showed ratios of R_θ/R_{20} of $4\cdot04$, $4\cdot1$ and $4\cdot31$ just before melting. At 90% minimum fusing current this analogue shows that the shape of the temperature distribution curve similar, i.e. C and D may be considered unchanged but t amplitude, B, is less.

Fig. 2 shows that for No. 29 S.W.G. copper wire carrying 90 minimum fusing current, $R_\theta/R_{20} = 2\cdot5$, and hence from eqn. (1

$$2\cdot5 = 0\cdot924 - 4\cdot81B - 1\cdot78B$$

so that $B = 0\cdot52$ and the maximum element temperature 52% of the melting temperature. This is in fairly good agre ment with Fig. 13. At $0\cdot073$ sec after switching off this curre R_θ/R_{20} can be seen from Fig. 2 to be $2\cdot34$, and from eqn. ($B = 0\cdot48$. The fall in temperature at the centre of the wire thus 4% of the melting temperature in this interval of $0\cdot073$ se

(10.2) The Effect of Pre-Loading on Temperature Distributi at the Time of Melting

A fuse initially unloaded, subjected to a heavy fault current has an almost rectangular temperature distribution at the mome of melting, as shown in Fig. 15(*a*).

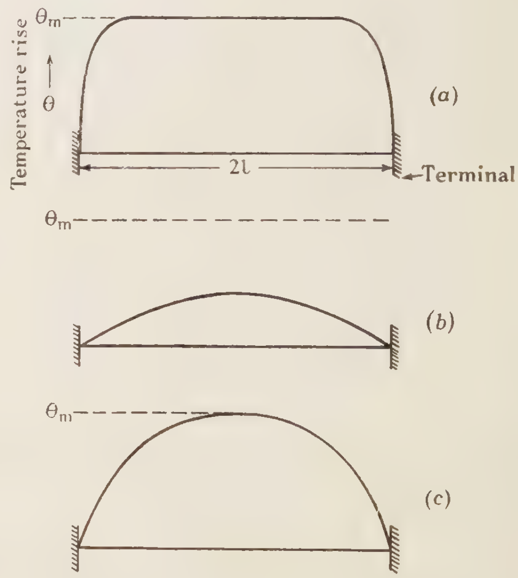

Fig. 15.—Temperature distribution along the length of the fuse element.

(*a*) Due to fault when unloaded.
(*b*) Due to load current.
(*c*) Due to fault when pre-loaded.

A pre-load current i (below the minimum fusing current) w set up a distribution of the form shown in Fig. 15(*b*).

When the pre-loaded fuse is subjected to the same total fau current I, the resulting temperature distribution must tend be more peaked than that shown in Fig. 15(*a*), and will be of th form shown in Fig. 15(*c*).

There are two reasons for this:

(*a*) The element centre is initially the hottest point and mu remain so, even with uniform heat generation.

(*b*) The resistivity, and therefore the heat generation, at the cent is initially, and therefore at all times, the greatest value througho the wire length.

This effect has been confirmed by means of the electric analogue, where two sets of currents were superimposed represent fault and load currents. This showed that, even up currents where the temperature distribution of the unloaded fu approached a rectangular shape, pre-loading caused the distrib tion at melting to be very similar to the peaked form set up by th minimum fusing current.

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Paper No. 1768
Feb. 1955

CHARACTERISTICS OF THE MOLYBDENUM-DEPOSITING ARC AND THE METAL-ARC MELTING PROCESS

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(*The paper was first received* 31*st March, and in revised form* 23*rd September*, 1954.)

SUMMARY

The arc melting of metals such as molybdenum, using the consumable-electrode process, is described. After a discussion of the nature, the shape and the stability of the arc, consideration is given to its behaviour inside a water-cooled copper mould when using a.c. and d.c. power supplies both under vacuum and in an argon atmosphere. The effect these factors have on ingot quality and on mould life is also discussed. The cause and detrimental effects of an unintentional electrical discharge which occurred in a prototype melting-plant are described in detail, and suggestions are made for minimizing the occurrence of the phenomenon. Experiments have been conducted to determine certain relationships between arc voltage, gas pressure and arc length for the high-intensity low-pressure molybdenum-depositing arc. The shapes of burn-offs are related to the current supply used: electrode-negative burn-offs are of two principal types, one conical and the other characterized by two drip-points; electrode-positive burn-offs have hemispherical ends; and a.c. burn-offs have almost flat ends. A theory is suggested to explain the configurations. The relationship between burn-off rate and current has been determined over a wide range of conditions; globule size was found to be related to the type of power supply used, and an explanation of this is included.

(1) INTRODUCTION

The production of solid masses of metals such as molybdenum, tantalum and tungsten in a high state of purity is not possible at present by a conventional melting and casting process, the fundamental difficulty being the lack of a suitable high-temperature refractory material. Commercially they are all produced by the powder-metallurgy method of pressing and sintering and are then hot-worked into the required form. This process has limitations, particularly regarding the maximum size of bar which can be pressed and sintered to yield a final product with satisfactory properties.

The heat of the electric arc has been used for melting metals for at least 70 years; the melting of a refractory metal, tantalum, was first reported by von Bolton in 1905.[1] Since then Kroll,[2] and later Radtke, Scriver and Snyder[3] developed the process for melting titanium by using water-cooled copper as a crucible. Parke and Ham[4] developed a consumable-electrode process for arc melting and casting molybdenum in a cylindrical water-cooled copper mould, and the most recent published work on this subject is by Hopkin, Jones, Moss and Pickman.[5]

In the consumable-electrode arc-melting process the metal to be melted is obtained in the form of a rod, which may be made by the powder-metallurgy technique and is contained in a chamber either under high vacuum or filled with an inert gas. The rod is connected to a source of alternating or direct current and is fed down centrally inside a water-cooled copper mould at the base of which is a disc of similar material forming the other electrode. When the two make contact a depositing arc is initiated and the rod material melts off, forming a pool of molten metal on the disc which eventually extends to the wall of the mould. Owing to the high thermal conductivity of the copper and the rapid heat extraction, the molten metal freezes rapidly as it comes into contact with the copper and no melting of the copper takes place. As more molten metal is added to the pool, progressive solidification takes place from the bottom and sides of the melt, so that at any instant only a small crescent-shaped pool of metal is molten.

The nature of the process makes it particularly useful for the melting and casting of a wide range of metals and alloys in a high state of purity. It is also possible by multiple remelting to reduce the content of gaseous and volatile impurities to a very small amount.

Only the electrical aspects of the arc melting of molybdenum are considered in this paper. A detailed metallurgical study of the process, together with some aspects of plant design, has been given by Hopkin, *et al.*[5]

(2) ELECTRICAL CONDITIONS

There is little published information concerning the behaviour of high-current-density metal-depositing arcs running at low gas pressures. Some work was therefore carried out on the electrical characteristics of such arcs over a range of pressures. The prime object was not to make a direct contribution to pure arc physics, but to obtain data pertinent to a better understanding of the arc-melting process.

(2.1) Power Sources

In view of the close similarity between the metal-melting process under discussion and ordinary metal-arc welding, standard welding equipment was used for the power sources. The d.c. supply was obtained from two or sometimes three drooping-characteristic welding generators coupled together in parallel; the maximum open-circuit voltage was 90 volts and the maximum current output was approximately 2kA at an arc voltage of 30 volts. The a.c. power source was a 90kVA multi-operator arc-welding transformer with an open-circuit voltage of 100 volts.

(2.2) The Nature of the Arc and the Influence of Arc Conditions on Molybdenum Melting in Vacuum and in Argon

The arc is an electrical discharge between electrodes and is usually considered to have a voltage drop at the cathode of the order of the least ionization potential of the gas or vapour in which it operates. Recent work, however, indicates that this is not necessarily true in all cases and that the arc is more complicated than is generally believed. The arc consists of three basic parts: the anode area, the cathode spot and the positive column or plasma. In the cooler zone surrounding the positive column, recombination of atoms takes place with the release of heat; this zone is known as the *aureole*. Cobine[6] has suggested that the temperature of the positive column may be as high as 11 000°K for a 200amp arc in air at atmospheric pressure. The cathode is heated by the bombardment of its surface with positive ions, and the anode is heated by electron bombardment. The stability of the cathode spot is greatly influenced by the chemical and physical conditions of the electrode.

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.

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At the outset it was not known whether direct current with the consumable electrode negative or positive, or alternating current, would be the most suitable for the arc melting of molybdenum; Parke and Ham[4] used the latter and no mention was made in their paper of the use of direct current. The optimum current density and arc voltage were not known and no information was available about burn-off rate, the effects of spatter or of very low pressures upon the behaviour of the arc.

It is thought that the d.c. arc is not parallel over its whole length, and it is suggested that the apparent visual parallelism frequently observed is caused by obscuration of the positive column by the *aureole*. The arc is believed to be trumpet shaped, supporting evidence being found in the fact that the cathode spot is very small in comparison with the anode area. Several measurements made in the course of this work have indicated cathode-spot areas of less than one square millimetre, corresponding to a current density of the order of 120 kA/cm^2. Until the position regarding anode "spots" is further elucidated, it is assumed, as in the past, that there is no clearly defined conducting area at the anode corresponding to that of the cathode spot, so that only an approximate current density can be stated. Determinations made from marks left on electrodes showed areas of 150–300 mm^2 corresponding to current densities of 1 000 and 500 amp/cm^2 in the extreme cases. From the sizes of the anode area and the cathode spot it might be inferred that the arc is shaped like the frustum of a cone, but this is not so, since over the majority of its length, the arc will be squeezed inwards by constrictive forces set up by its magnetic field, thus producing a trumpet shape. Confirmation of this has been given by Gillette and Breymeir,[7] who found from photographic studies that the arc plasma is definitely bell-shaped and not cylindrical, as had generally been assumed in the past.

For convenience in following the ensuing discussion, a simplified schematic of the melting plant is given in Fig. 1.

During operation with the consumable electrode positive the cathode spot can wander from the base disc on to the vertical walls of the copper mould; when this occurs the spot occasionally stops tracking and becomes fixed. On account of the very high current density, local melting of the water-cooled copper is then liable to occur and the molten molybdenum flows into the resultant craters, producing mechanical locking which impairs ingot removal; in a few instances moulds have been so badly scored as to render them unserviceable. When the consumable electrode is negative the copper moulds do not suffer such damage, because the current density at the anode is relatively low, so that if the anode spot should wander, only a comparatively gentle heating influence is exerted and local overheating is prevented by the rapid heat transfer through the water-cooled copper. Under these conditions mould damage is likely to occur only if insufficient cooling water is used.

It has been observed that there is a much greater tendency for cathode spot and consequent arc wandering to take place with the consumable electrode positive than with it negative. This is especially true when the electrodes, as well as the surrounding copper, are cold and covered with films of impurities, which seem to persist even after careful cleaning. Arcs have been seen to wander up and out of moulds, where they either extinguish or develop into stable arcs. The end of the consumable electrode heats up more quickly than the base disc electrode, because it is of smaller dimensions and is not water cooled; a stable arc is therefore created more speedily when the former is negative than when it is positive. This could be expected, for arc stability is dependent on an adequate supply of electrons from the cathode spot and is therefore a function of temperature. The anode end of an arc is quite stable and rarely wanders unless caused to do so by movement of the cathode spot.

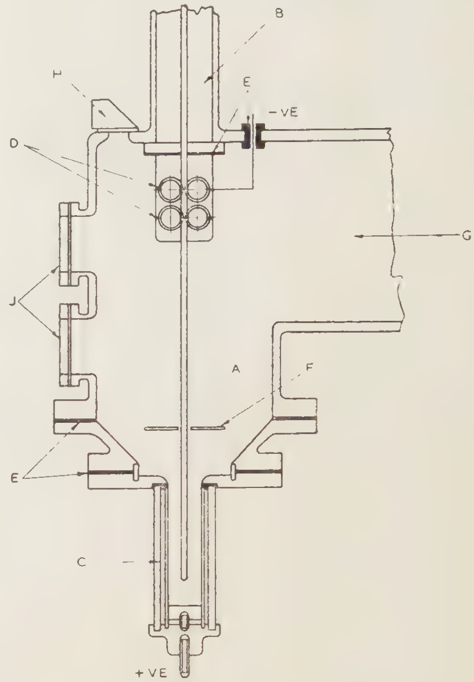


Fig. 1.—Schematic of the arc-melting plant.

A. Melting chamber.
B. Extension tube for electrode.
C. Water-cooled copper mould.
D. Electrode drive mechanism and conductor rolls.
E. Insulators.
F. Spatter shield.
G. Vacuum line.
H. Periscope.
J. Windows.

Once molten metal is deposited on the base, arc stability is enhanced considerably; another factor which influences arc stability is the shape of the pool in relation to the arc length, since this affects cooling conditions.

From the experimental work so far carried out it can be stated that the ability to produce satisfactory ingots is a function of several factors, namely the type of current supply, the current density, the arc stability, the arc length and the pressure. The relationship between the last two factors is discussed in detail in Section 2.4.

With an a.c. supply and electrodes of 1 cm diameter, there was very good arc stability above 900 amp. For routine ingot production, currents as high as possible must be used, not only on account of the higher burn-off rate, but also because currents lower than 1·2 kA result in ingots having unsound outer zones. Recent work has indicated that by the time the very small globules reach the mould wall their temperature is below that necessary for adequate liquid flow, so that cold-shuts occur.

With a d.c. supply and the consumable electrode positive, very satisfactory melting takes place at currents higher than 800 amp so long as the cathode spot does not wander. From the standpoint of surface quality of the ingot, a current of between 1 and 1·3 kA is best, but the surface quality is inferior to that of ingots produced with a d.c. supply and the consumable electrode negative. Apart from this consideration, the converse operation is not recommended, owing to the probability of mould damage from cathode-spot wander.

When using a d.c. supply with the consumable electrode negative, arc stability is excellent above about 800 amp. Practically all melting is now done at 1·2–1·3 kA d.c., with the

consumable electrode negative, because of the higher burn-off rate and improved surface quality of the ingot.

The use of currents below the optimum range results in inferior ingots with a surface of poor quality. A current somewhat higher than that necessary to produce flow to the mould walls does not cause any noticeable difference in ingot quality nor in grain structure as a result of the larger molten pool. A current greatly in excess, however, causes molten metal to be blasted up the sides of the copper mould to form an overhang, which results in heterogeneous crystal structure and may in extreme cases lead to side arcing; the normal molten-pool formation ceases in this event and melting must be terminated to avoid serious damage to the mould. It is also important that the correct arc length should be used in conjunction with a current density within the optimum range. An excessive arc length results in a reduced radial flow of molten metal, owing to the small heat content of the pool, and is analogous to an insufficient current density. Too short an arc is likewise analogous to an excessive current density and leads to similar undesirable results. Currents higher than 1·3 kA, using an arc length of $\frac{3}{4}$ in, are not advisable when using $1\frac{3}{4}$ in-diameter moulds.

There is a definite relationship for a given arc length between the current and the free-flow diameter of the molten metal, and the maximum mould diameter for satisfactory ingot production is governed by these factors. The minimum mould diameter is controlled by loss of arc stability due to surface deionization and by mechanical choking of the arc in very small moulds. There is, of course, also an increased tendency for side arcing on to the mould in such conditions.

It was expected that the characteristics of the molybdenum-depositing arc running in argon would be different from those obtaining in vacuum, whatever the pressure of the argon. Some information is available on the behaviour of metal-depositing arcs in various gas atmospheres at atmospheric pressure as a result of the application of gas-shielded arcs in the welding of metals. When an arc is struck in an atmosphere containing molecules of diatomic gases, whether at high or low pressure, some of the energy of the arc is used in dissociating the molecules, this energy being released again in the outer zones of the arc, where recombination of the atoms takes place. The result of this process is a wider distribution of the heating effect of the arc. For arcs in monatomic gases, such as argon and helium, no such effect can occur, which may be one reason for the small free-flow diameter of the molten pool found in such cases.

The first experiments in argon atmospheres were made at atmospheric pressure using direct current with the consumable electrode negative—the best supply for melting in vacuum, but the burn-off rate with a 20-volt 1·5 kA supply was only 3·53 g/sec. Because of this the polarities of the electrodes were reversed and the test was repeated with the same current; the burn-off rate was almost exactly doubled, but the flow of molten metal to the mould wall was still insufficient, resulting in an ingot of irregular surface.

The inadequate flow of molten metal to the mould wall may also be partly due to the additional heat losses by convection; to obtain a total power input higher than that normally used in vacuum melting, currents exceeding 2 kA must be used. The use of 2·2 kA with the consumable electrode positive gave an ingot which filled the mould, the arc voltage being 25 volts and the burn-off rate 14 g/sec. It is thought that the use of slightly higher currents will be beneficial, although 2·2 kA is nearly the maximum current which the 1 cm-diameter electrode will carry without serious overheating.

No evidence of serious cathode-spot wander was encountered in melts in argon, in contrast to the behaviour of d.c. electrode-positive arcs in vacuum.

All ingots produced in argon have had an almost flat crater on the top, in contrast to the marked concavity of craters in ingots melted in vacuum.[5]

(2.3) Secondary Electrical Discharge encountered in Vacuum Melting

The most serious operating trouble encountered in the early development of the plant was an electrical discharge between the electrode and various parts of the plant. This trouble was encountered in one of the first experiments in the original prototype apparatus. In this experiment the d.c. electrode-positive arc was used and melting proceeded satisfactorily until near the end of the run, when the arc voltage suddenly became erratic; a fernlike marking was noticed on the top of the mould after dismantling. The first series of experiments in a larger plant were all accompanied by this phenomenon, the markings occurring either up the length of the electrode or on various parts of the melting chamber, whichever was at the negative potential. It was then apparent that the markings were due to a wandering electrical discharge and, moreover, that it would have to be eliminated before satisfactory ingots could be melted.

It is not possible to say with certainty whether or not this type of discharge took place simultaneously with the main arc. Visual observation indicated that in some cases it did so and that in others the main arc was extinguished. Before the cause of the trouble was discovered, various forms of grid and screening arrangements were tried, either insulated or charged to various potentials. Observation of the fact that the track marks of the discharges often appeared to start at a globule of spatter showed how the problem could be solved.

Spatter can be projected either from the electrode tip or from the molten pool beneath it, and can travel out from the vicinity of the arc at any angle. It is now thought that the initial cause of the discharge was the bridging of the gap between parts at opposite potentials by a globule of spatter or the vapour from it. The temperature of such spatter would be close to the boiling point of molybdenum (5 000°C), and on passing through the high vacuum it would leave a trail of molybdenum vapour which would become positively charged as a result of thermionic emission and could drift electrostatically to parts at negative potential. This view has recently been substantiated partially by the work of Gillette and Breymeir,[7] who, as a result of cinematographic studies, concluded that the arc contains luminous metal vapour and that droplets of molten metal in free flight are normally surrounded by luminous vapour sheaths.

The track marks were caused by wander of the cathode spot. This must have had a high velocity, for in spite of its intense local heating effect, most of the individual tracks bore no visible sign of fusion. Occasional evidence could, however, be seen of momentary fixing of the cathode spot causing melting and producing craters, probably at areas favouring high electron emission. When the consumable electrode was negative, marks due to the anode area on the walls of the chamber were also observed. These marks were of a different nature and indicated that the anode end of the arc did not wander much during the discharge.

A secondary discharge of this type may possibly develop into an arc of higher intensity than the original, but this is unlikely and more often it will become unstable and extinguish because of the long positive column.

In the present plant, as shown in Fig. 1, the whole chamber and the larger area of the base-plate have been insulated from both the electrode and the drive mechanism and from the mould, so as to reduce the possibility of spatter bridging the gap between parts at opposite potentials. In addition, care has been taken to avoid the use of low-work-function materials (e.g. silver

solders containing cadmium) and those likely to have high vapour pressures when heated, since arcs of low voltage may result from their use. These precautions have eliminated the trouble.

(2.4) **Electrical Characteristics of the Molybdenum-Depositing Arc at Low Gas Pressures**

When the preliminary tests were being conducted it was noted that the behaviour of the voltage on arc lengthening was different from that encountered with arcs in air at atmospheric pressure. Since consideration was to be given to the design of an automatic drive for feeding down the electrode, a series of experiments was conducted to obtain an approximate idea of the variations of voltage with arc length and pressure. Without some indication of the required sensitivity it would have been difficult to design a control.

Since the information required was to be used for practical purposes, it was decided to imitate the actual operating conditions so far as possible. In the absence of any more reliable experimental approach, the arc-lengthening technique was employed, i.e. that of drawing out the arc and measuring the variables.

In these experiments a flat steel base-plate replaced the conical base-plate shown in Fig. 1. A disc of sintered molybdenum $1\frac{1}{2}$in in diameter and $\frac{1}{2}$in thick was fixed in a copper clamp attached centrally to the inside of the base-plate. Thus arcing took place on a flat disc without the confining effect of the mould which exists during ingot production.

Before each experiment the chamber was evacuated to the required pressure and the tip of the electrode was machined to a 60° cone to facilitate striking of the arc. The electrode was fed down by hand until contact arcing commenced; it then remained stationary and burned off, so that the arc length increased continuously until the termination of the test. During each test run the voltage was autographically recorded and current and pressure readings were taken at least every second. A voltage recorder with a capillary ink pointer-arm was used, although this instrument did not give strictly accurate striking voltages, owing to its time lag; full-scale deflection took approximately 0·1 sec, so that the initial inaccuracy was of short duration and was a constant factor in all tests.

The results given in this Section and shown graphically in Figs. 2–7, represent data collected during 185 tests. It was not practicable to include all individual results, but those of one experiment, using a d.c. electrode-negative arc at an open-circuit voltage of 90 volts, are reproduced in Table 1.

The voltages given in Table 1 were obtained from the autographic record, the term "voltage" being used to include arc voltage and voltage drops in the various leads and connections. The latter amounted to about 1·5 volts and was a constant factor in all tests.

The method used to derive the values given in the last two columns of Table 1 is described below.

The values of burn-off rate corresponding to the current readings in the previous column were obtained by reference to Fig. 2, which shows the relationship between burn-off rate and current for the d.c. electrode-negative arc. The weights of metal melted given in the succeeding column were obtained by summation of the amounts melted for each increment of time. The final derived weight, however, did not always correspond to the

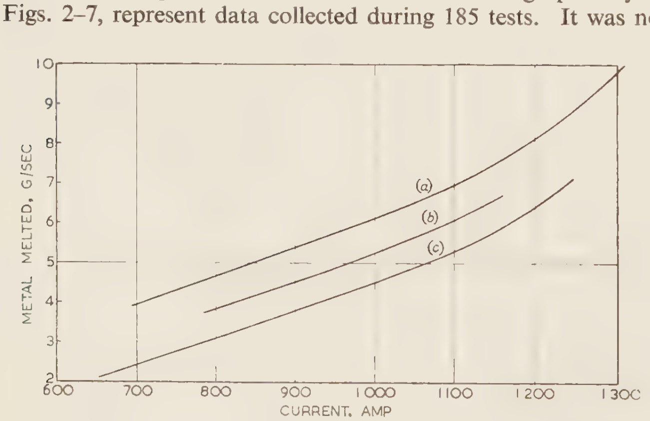


Fig. 2.—Burn-off rates for 1 cm-diameter molybdenum electrode.
(a) D.C. arc, consumable electrode negative.
(b) A.C. arc.
(c) D.C. arc, consumable electrode positive.

Table 1

Time	Voltage	Pressure	Current	Burn-off rate	Derived metal melted	Derived arc-length
sec	volts	mm Hg	amp	g/sec	g	mm
0	26·3	0·009	1 020	—	—	—
0·5	27·0	0·0095	1 018	6·4	3·2	7·0
1	27·6	0·010	1 015	6·4	6·4	10·2
2	28·4	0·012	1 010	6·4	12·8	16·6
3	29·0	0·014	1 008	6·3	19·1	22·9
4	29·3	0·017	996	6·2	25·3	29·2
5	29·7	0·022	990	6·2	31·5	35·4
6	30·0	0·030	985	6·1	37·7	41·5
7	30·3	0·042	978	6·1	43·7	47·5
8	30·8	0·06	972	6·0	49·8	53·4
9	31·2	0·09	966	6·0	55·7	59·2
10	31·8	0·13	960	5·9	61·7	64·9
11	32·8	0·2	954	5·9	67·6	70·5
12	33·6	0·3	948	5·8	73·4	76·0

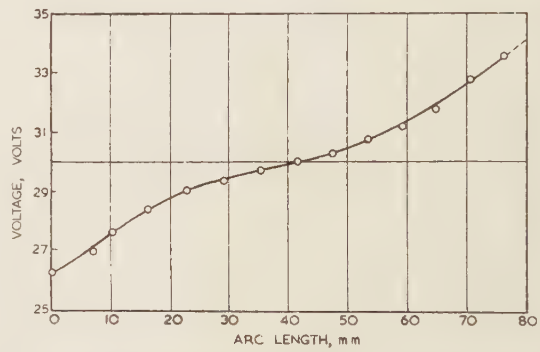


Fig. 3.—Relationship between arc length and voltage; d.c. arc with consumable electrode negative.

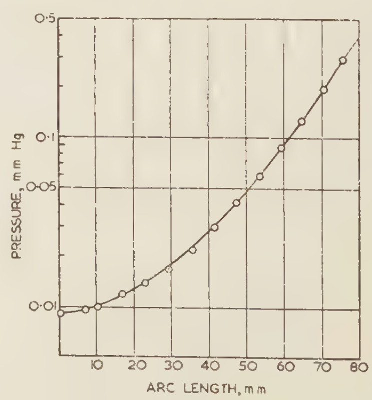


Fig. 4.—Relationship between arc length and pressure; d.c. arc with consumable electrode negative.

actual weight of metal melted, as found by weighing the electrode before and after melting; this discrepancy was of the order of a few per cent, and a correction was therefore made to all values in the derived-weight column in Table 1, assuming a proportional error between actual and derived weights. The arc length was then determined by constructing a plotting relationship between the length of a conical-tipped electrode and its weight; the arc lengths corresponding to the corrected derived weights of metal melted were then read off.

The arc-lengths derived in this manner were then plotted against voltage and pressure (Figs. 3 and 4); the voltages and pressures for certain lengths are given in Table 2. Thus, for

Table 2

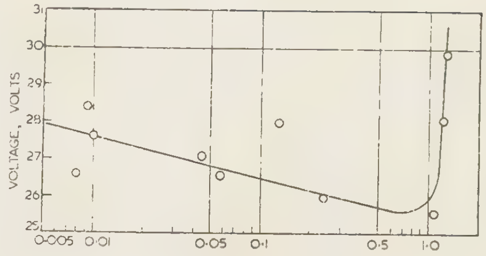
Arc length	Voltage	Pressure
mm	volts	mm Hg
0	26·3	0·009
5	26·8	0·009
10	27·6	0·010
15	28·2	0·010
20	28·8	0·013
25	29·2	0·015
30	29·5	0·018
40	30·0	0·028
50	30·5	0·050
60	31·4	0·095
70	32·7	0·2
80	34·2	0·4

any arc length each experiment gives one point on a curve relating voltage and pressure. From numerous experiments with different starting pressures other points were obtained, and so graphs of voltage against pressure were constructed for each arc-length. Examples of such graphs are given in Fig. 5. The curves for each arc-length are shown superimposed in Fig. 6(*b*). This indirect experimental method was necessary, since the pressure could not be held constant during a run because of gas evolution.

The characteristics of d.c. electrode-positive, d.c. electrode-negative and a.c. arcs were studied by this method. The graphs of voltage against pressure for these three conditions (Fig. 6) revealed surprising differences, the most notable of which were: (*a*) the marked difference in rate of change of voltage with pressure between d.c. electrode-positive and d.c. electrode-negative arcs at pressures below about 1 mm Hg; (*b*) the sudden increase in voltage with increasing pressure which occurs for all arcs at about 1 mm Hg pressure; (*c*) the gradual decrease of voltage as pressure decreases below about 1 mm Hg for the a.c. arc, contrasted with the increase of voltage for the d.c. arcs; (*d*) the high starting voltage for the a.c. arc compared with the lower voltages for 5 and 10 mm d.c. arc lengths.

Fig. 6(*a*), for the d.c. electrode-positive arc, shows that the rate of fall of voltage with increasing pressure, below about 1 mm Hg, is constant at arc lengths of less than 50 mm, decreases up to 100 mm and becomes negative for longer arcs.

From Fig. 6(*b*) it is seen that, at pressures in excess of 1 mm Hg, where the sudden increase in voltage occurs, the individual curves for different arc lengths blend into an almost vertical band. From the known behaviour of arcs at atmospheric pressure it is apparent that the curves must flatten out and spread at pressures higher than those shown. The individual curves in Fig. 6(*a*) do not blend into a band, but they might have done so in a manner similar to those already discussed had experiments been carried out at higher pressures. There is an indication of this occurring for arc lengths of from 70 to 120 mm.



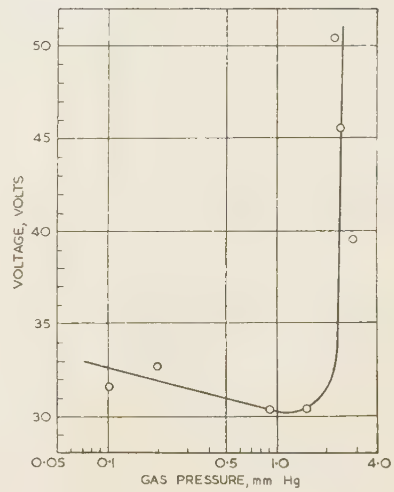
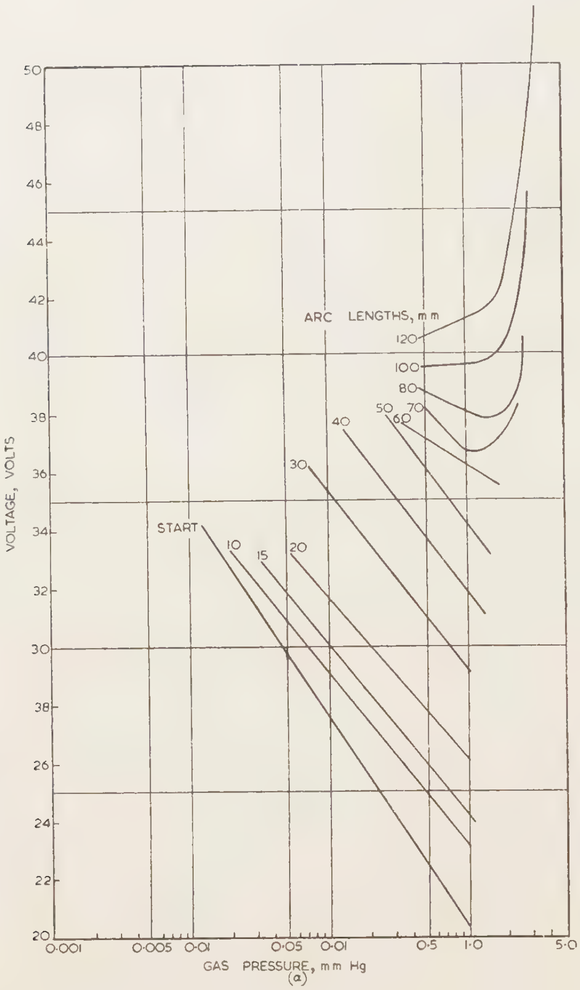


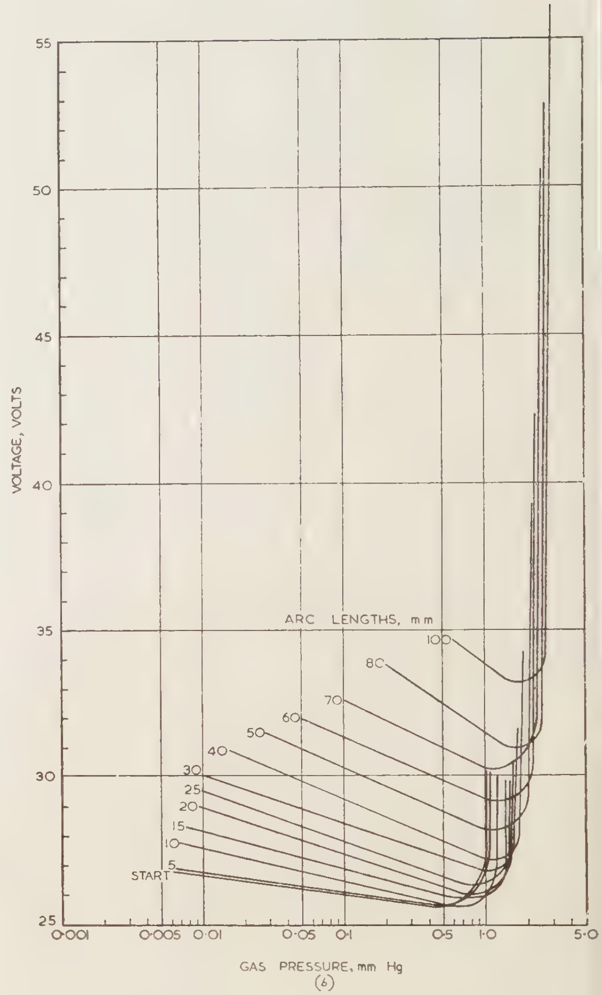
Fig. 5.—Effect of pressure on voltage of d.c. arc with consumable electrode negative.
(*a*) 10 mm arc.
(*b*) 70 mm arc.

Pressure readings in the region of 1 mm Hg, where the curves show the marked inflection, were not accurate owing to the low sensitivity of the Pirani gauge in this region.

Figs. 7(*a*), 7(*b*) and 7(*c*), which are derived from Figs. 6(*a*), 6(*b*) and 6(*c*), show the variation of voltage with arc length for several pressures. In contrast to the curves for d.c. electrode-positive arcs, those for d.c. electrode-negative and a.c. arcs are relatively flat. The curves for a.c. arcs are characterized by troughs for short arc-lengths at pressure below 0·5 mm Hg, on account of the higher starting voltage, previously mentioned.

Since the work described above was completed, a much improved vacuum system has been brought into use, and many melts have been carried out with d.c. electrode-negative arcs at starting pressures of between 0·01 and 0·05 micron Hg, and a correspondingly steady running pressure of about 0·1 micron Hg. This work was not done with the particular object of studying electrical characteristics of the arc, but data on arc voltage, current and pressure have been recorded. These data are not reported, owing to the large scatter of arc voltage found in different experiments; for example, for pressures of the order of 0·05 micron Hg a range of 7 volts was found. The higher voltages within this range were found to fit reasonably well to the extrapolated curves in Fig. 6(*b*). It appears that, other conditions being similar, some slight variation in chemical or physical constitution between different batches of nominally pure molybdenum rod is sufficient to cause an appreciable change in arc voltage. In connection with both this and the following Section, it is interesting to note Mason's suggestion[8]





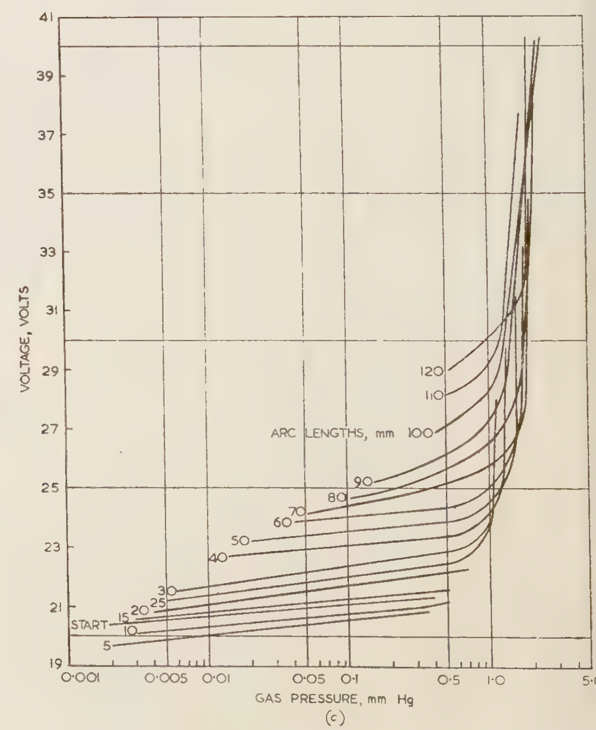


Fig. 6.—Effect of pressure on total voltage for arcs of various lengths.

(*a*) D.C. arc with consumable electrode positive.
(*b*) D.C. arc with consumable electrode negative.
(*c*) A.C. arc.

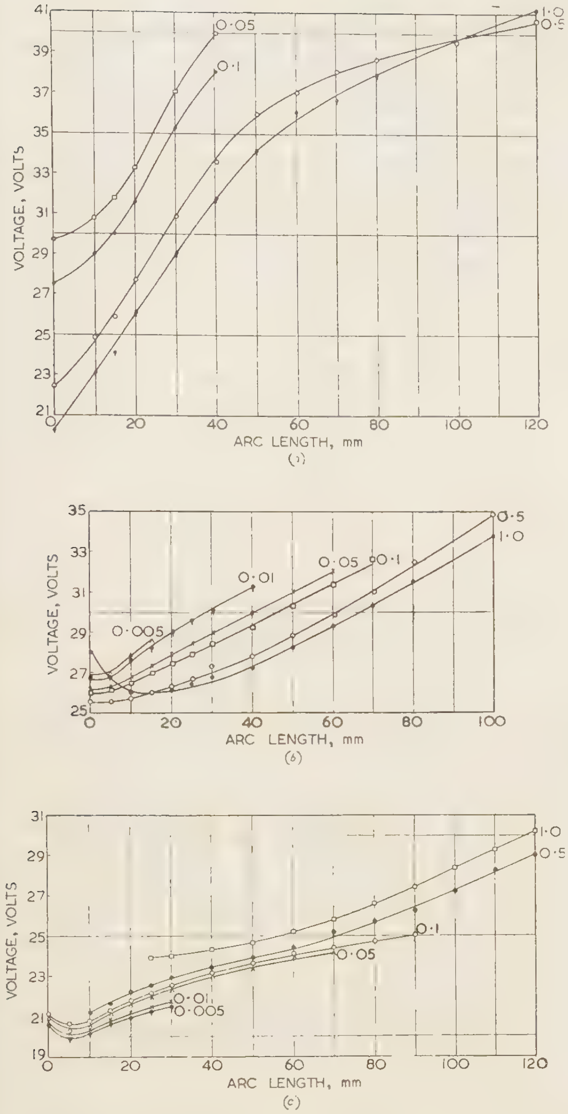


Fig. 7.—Effect of arc length on total voltage at various gas pressures.

(a) D.C. arc with consumable electrode positive.
(b) D.C. arc with consumable electrode negative.
(c) A.C. arc.

hat field-emission arcs may occur with pure materials and hermionic-emission arcs with impure ones, and that the voltage f the former is at least 4–6 volts higher than that of the thernionic arc.

(3) CHARACTERISTICS OF THE BURN-OFF PROCESS

(3.1) The Shape of Molybdenum Burn-offs

It has been observed that the shape of molybdenum burn-offs, e. the tip or end portion of a consumable electrode with which he arc is in contact at the conclusion of a melt, is related o the polarity of the current supply used. With d.c. electrode-ositive arcs, smooth, almost hemi-spherical, burn-offs are prouced, as shown in Fig. 8(*a*). The burn-offs from d.c. electrode-egative arcs are of two main types, one conical in form Fig. 8(*b*)] and the other characterized by two "drip points" with valley between them [Fig. 8(*c*)]. Burn-offs from a.c. arcs have lmost flat ends [Fig. 8(*d*)]. Some burn-offs, while actually elonging to the above groups, are not always readily recognized

(*a*) (*b*) (*c*) (*d*)

Fig. 8.—Typical molybdenum burn-offs produced at 1 kA.

(*a*) Consumable electrode positive.
(*b*) Conical type, consumable electrode negative.
(*c*) Two-drip-point type, consumable electrode negative.
(*d*) A.C. arc.

as such from their outward appearance. For this reason care must be exercised in examining them, since their geometry can be changed considerably by metal flow and gas evolution after extinction of the arc.

In view of the trumpet-like form of the arc, the shape of the positive burn-off could be expected, since it is bathed, at least over the whole area of its tip, in a heat source of relatively low intensity. Similarly the flat a.c. burn-off is not surprising, in view of the alternations of two different heat sources. No simple explanation of the dissimilar types of electrode-negative burn-offs is apparent, but a tentative theory is developed below. Before discussing this it must be stressed that it is based chiefly upon evidence and observations obtained from over 500 actual plant operations and not from experimental work designed to elucidate the phenomena. However, it is considered that the information and deductions presented will serve as a discussion point and may also guide the planning of a more detailed fundamental research as well as being of immediate practical use.

The configurations of the electrode-negative burn-offs are obviously due to a systematic wandering of the cathode spot; the problem is to determine why it traverses such paths, which seem to be caused by a combination of vertical and rotary forces. The latter would appear straightforward, since it is known that an arc may rotate when subjected to a transverse magnetic field; the movement can be caused by either the arc-current's own magnetic field or that from an external source. The velocity is particularly influenced by magnetic field strength, arc current and gas pressure.

An arc between an electrode and a pool of metal at atmospheric pressure will normally function between the tip of the electrode and the surface immediately beneath it, because (*a*) the smallest gap in the system usually corresponds to the lowest voltage, (*b*) an arc tries to follow a path in line with the axis of the electrode, and (*c*) the temperature at the tip of the electrode will be greater than that at any other position. The last factor is of particular importance, since thermionic emission increases exponentially with temperature, as shown by the Richardson–Dushman equation.[9] Both field and thermionic electron emission from nominally pure metals are influenced by the impurities present and also by any adsorbed and absorbed gases; the classic instance of the effect of a small amount of thoria, or of alkaline oxides, in tungsten is a well-known example

of this phenomenon. On the assumption that the chemical composition of the electrode under consideration is graded from 100% pure metal at the tip to something inferior a short distance from it, it is possible to visualize that an arc running from this impure point to the pool of metal will do so at a lower voltage than one from the tip to the pool, owing to the more favourable electron emission, even though the temperature will be lower and the arc longer. By being heated at a high temperature and in a low gas pressure such a graded electrode is, in fact, produced as a result of outgassing and evaporation of impurities, as shown in Table 3.[10] The higher the temperature and the lower the gas pressure, the more effective is the purification, especially when melting occurs. Because such purification is dependent upon diffusion, time will be of importance, so the outer layers will be purified more quickly than the interior ones and small sections more quickly than large sections.

Table 3

State of molybdenum	Amounts of impurities					
	Oxygen	Hydrogen	Nitrogen	Carbon	Iron	Silicon
	%	%	%	%	%	%
As received (powder metallurgy)	0·0019–0·015	0·00004	0·0008	0·003	0·020	0·002
Solid state, purified at 1 925°C	0·0003	0·00002	0·0002	0·003	0·020	0·002
Cast from the fused state	0·0002	0·00005	0·0002	0·002	0·001	0·0005

The work function of metals in general is profoundly affected, not only by the amount, but by the nature and distribution of impurities or surface contaminants. Usually, electropositive elements decrease the work function (i.e. greater emission) and electronegative elements increase it (i.e. smaller emission). Reimann[11] has pointed out that molybdenum holds on tenaciously to surface contaminants and that adsorbed oxygen is particularly difficult to remove. After using a mass spectrograph, Grover[12] concluded that it was almost impossible to remove all traces of the potassium impurity from molybdenum by solid-state purification.

Martin[13] obtained a work function of 3·48 volts for molybdenum after outgassing at 1 700°K, while Du Bridge and Roehr[14] obtained 4·15 volts after outgassing at up to 2 100°K. Although different specimens were used, the difference can most likely be attributed to outgassing and is confirmed by the interesting fact that in the early stages of the latter's investigation the work function was similar to that which Martin had reported. Values higher than the above have been obtained, but some of these at least may also be explained by outgassing phenomena, since Du Bridge and Roehr also found increases before the completion of outgassing. Variations of a similar nature have been encountered by Sende and Simon[15] in the photoelectric emission from platinum. The truest value for the work function of "pure" molybdenum is likely to be obtained from material which has undergone outgassing and purification in the molten as well as in the solid state.

The conditions prevailing at a burn-off can now be considered in detail. Here, under normal operating conditions, the tip will be at the highest temperature, and because metal purity increases with temperature, it will also have the highest work function. Therefore, the greatest emission may come, not from the tip, which at first sight might be expected, but from some other position where, although the temperature is lower, the work function is lower. It is, then, conceivable that in moving ov equipotential surfaces an arc may oscillate between two positio corresponding to different arc lengths, if the delicate balance the variables is periodically upset by a systematic disturban such as globule detachment. The stability of an arc depenc not only upon its static characteristics, but also upon its dynam response to a disturbance. An arc operates at the lowest possib voltage, and this does not always coincide with the shortest a length. This is especially pronounced at low pressures, whe conditions for ionization are more favourable and result in ar having smaller voltage gradients.

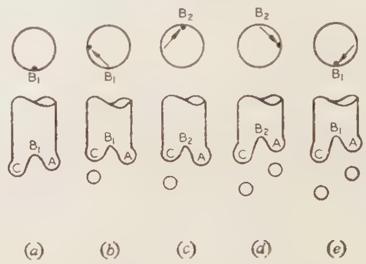


Fig. 9.—Schematic showing how the suggested movements of the a can produce a 2-drip-point burn-off.

The group of sketches in Fig. 9 illustrates the suggested a oscillations. Starting with the arc in position B_1 [Fig. 9(*a*) metal is being melted and simultaneously purified; part of th molten metal is transferred directly to the pool and part flov down and heats the solid portions of appendages A and (These will become longer as the groove being melted out by th arc at B_1 gets deeper. Because the thermal conductivity decreas with increase of temperature, and since the small-section appe dages are closer to the molten pool, the heat losses by conductic will be greater at B_1, where, in moving upwards, the cathode sp would encounter increasingly cooler metal. Electron emissic from the highly heated solid portions of the appendages would l very high, and probably higher than that from the more purifie liquid molybdenum at about the same temperature. If free t do so, a cathode spot will traverse surfaces at which conditio are most favourable for the greater electron emission. Onc such conditions at B_1 became inferior to those prevailing at (the cathode spot would move towards the latter. In doing so th tip would be melted off, as shown in Fig. 9(*b*), causing the a to move quickly up to B_2, as in Fig. 9(*c*), since being depriv of its hot spot, the remains of tip C would no longer be the mo prolific emitter. The foregoing event would then be similar repeated in respect of appendage A, Figs. 9(*d*) and 9(*e*), aft which the whole cycle of events would be repeated continuousl Evidence in the form of ripple marks has confirmed the gener trends of the above arc movements. The valley between th drip points generally falls along a diameter of the electrode.

Since the velocity of arc rotation and the extent of vertic movement are independently variable, the direction of th resolved arc path would be varied accordingly. This in tu would change the perimetrical distance at the lower end of a electrode between the points at which the arc completed o upward and one downward traverse. According to this arg ment, it should be possible to produce burn-offs having sever drip points. In fact, multi-drip burn-offs have been observe but they are not common; there are apparently two "equilibrium types, the 2-drip variety and the conical one. The predominanc of the 2-drip type amongst the non-conical burn-offs may ari because the combination of the various conditions usual employed is simply fortuitous in being approximately corre

for this type to form and that small differences in some variables are insignificant in affecting the general configuration. When particles of metal are melted away the geometric symmetry of the system is upset, causing distortion of the electric and magnetic fields around the electrode. These may be of importance, in some instances, in determining whether or not a 2-drip-point type of burn-off shall form. Since it is a flexible gaseous electrical conductor, the arc can be influenced readily by these,[16] especially when high currents are used.

When the velocity of rotation of the arc is appreciably higher than that pertaining to the formation of 2-drip-point burn-offs, the conical type results, owing to the progressive blending of the arc-melted grooves formed alongside one another. This blending is assisted by the melting away of high spots by superheated liquid metal as it washes over the surface. This type of burn-off usually bears evidence of some sloping individual grooves. As the gas pressure decreases the burn-offs become remarkably uniform, and no sign of grooving can then be detected. Evidence obtained from examination of many such specimens, together with visual observation of the arc, suggests that at very low gas pressures (such as 10^{-5}mm Hg) the arc rotates at a high velocity.

The meniscal bulge of metal which is usually present on the conical type of burn-offs shown in Fig. 10 is probably due to a combination of surface-tension forces and of high-temperature gas blasts from the pool acting on the evenly and highly heated liquid portion of the electrode. Meniscal bulges have also been encountered when using electrode-positive arcs at very high currents.

The burn-offs illustrated in Fig. 10 (see also Fig. 8) show that the depth of the groove between the drip-points and also the size of the cones can vary greatly. This can be accounted for by differences in the severity of the temperature gradient at the end of the electrodes. This is influenced by several factors, the chief ones being ohmic heating (current used and position of current entry to the electrode) and thermal heating (heat radiated from pool). Changes of arc length can affect the contour of the pool of metal by blast effect, the thermal radiation from it and, consequently, the temperature gradient in the electrode. This has been confirmed experimentally by metallographic examination, the distance between the points corresponding to 2 625°C (melting point of molybdenum) and 1 200°C (recrystallization temperature) having been determined and large differences found between the various specimens. Such variations lead to a greater or lesser degree of solid-state purification, and so the work function varies accordingly. Another fact, important when considering field emission, is that as the temperature increases the roughness of the surface also increases until incipient melting occurs.

Under normal conditions an arc would be expected to rotate in the same direction as that of the electromagnetic forces, as can be predicted. Instances of retrograde motion have been reported, but it is stated that thermionic arcs are not subject to such a reversal.[17,18] In the present work, with the consumable electrode negative, the arc, as viewed visually, has been seen to rotate in either the clockwise or the anti-clockwise direction; in some instances no rotation was observed. Fig. 11 shows photo-

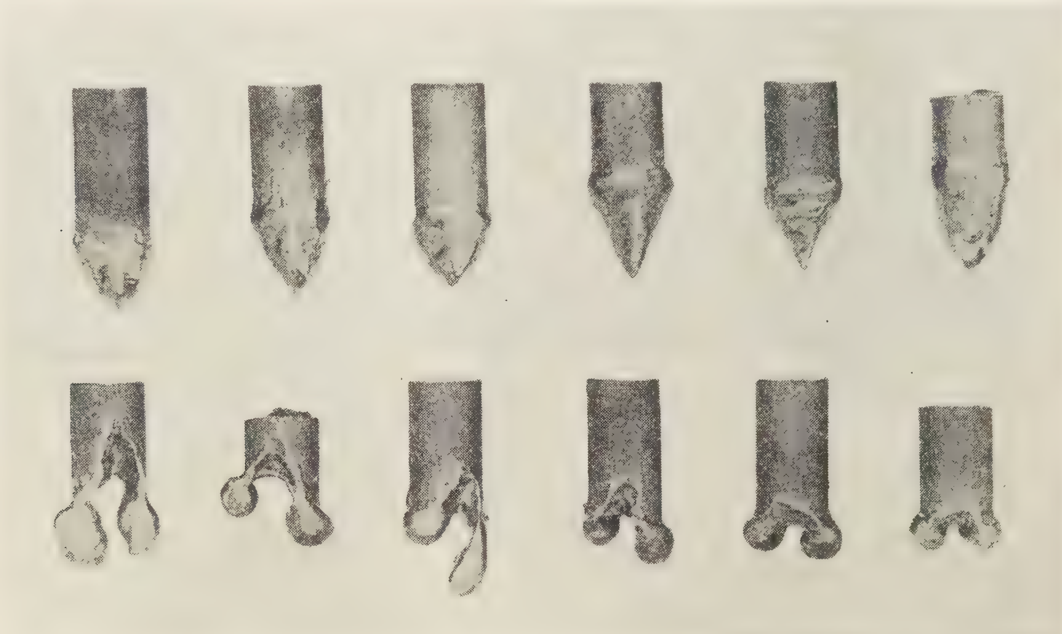


Fig. 10.—Photographs of the two main types of electrode-negative burn-offs showing the variations frequently encountered.

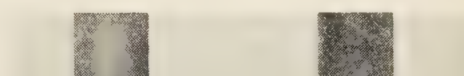


Fig. 11.—The direction of rotation of an arc can be clockwise or anti-clockwise as indicated by the burn-offs shown.

graphs and schematics of burn-offs from two routine experiments in which the correct and the retrograde rotation of the arc were clearly observed. The tangential direction of the detached globules can, without doubt, be visualized from the shapes of the drip points, which, as can be seen, are in opposite directions.

When a globule of molybdenum detaches from a drip-point the arc suddenly moves upwards, as explained previously. This increased velocity consequently influences the actual shape of the area around the drip-point, owing to dissimilar melting of the two sides, i.e. the resolved arc path is less steep as the arc descends than when, after globule detachment, the arc is ascending. Although most of the 2-drip-point burn-offs have shown such asymmetry, the effect is not usually as pronounced as in the examples shown in Fig. 11.

The various arc wanderings described above are not due to the feeding downwards of the electrode, since the phenomenon occurred regardless of feeding, i.e. electrode stationary with arc length increasing.

It may be mentioned here that several negative burn-offs were produced which gave interesting confirmation of selective electron emission. The cathode spot had at times wandered up and under the electrode's outer surface, as shown in Fig. 12. This could

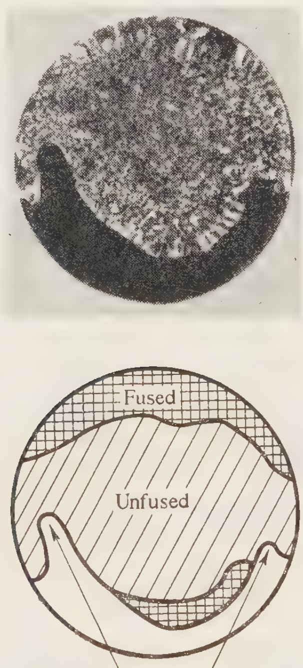


Fig. 12.—Movement of a cathode spot can occur under the outer surface of an electrode owing to selective emission.

conceivably have been caused by grain-size differences resulting from the heterogenity of mechanical work in producing round electrodes from square bars. This suggestion has now been confirmed partially by Kramer's work in a recently published article by Lintner and Schmid,[19] which states that emission can occur during the recovery and recrystallization of cold-worked metals and also during phase changes. There has not been time to estimate the significance of Kramer's work upon the research described in the paper, but it would seem to be of potential importance.

(3.2) Consideration of Burn-off Rates and of Globule Sizes

The burn-off rate of the electrode increases with current and is related to other electrical conditions. Fig. 2 shows the burn-off rates for a.c. and d.c. arcs operating in vacuum, plotted against current.

Efforts were made to determine the effect of gas pressure upon the burn-off rate when the consumable electrode had negative polarity, but within the pressure range of 0·1–0·001 mm Hg no significant difference was observed. Scatter of results was less noticeable at the higher pressures; this may be linked with the residual-gas content of the electrode having a more pronounced effect at the low pressures.

Arcs appreciably longer than those used for ingot production result in a slightly decreased burn-off rate. Calculations of melting efficiency show that this is approximately 22% for d.c. electrode-positive arcs and 26% for d.c. electrode-negative arcs.

The burn-off rates, together with size and weight ranges of globules collected after melts with the three types of electrical supply using a 1 cm diameter molybdenum electrode, are given in Table 4. The figures for d.c. electrode-negative arcs are for the 2-drip-point type of burn-off.

Table 4

Burn-off Data for 950 amp Arcs

Supply	Polarity of consumable electrode	Burn-off rate	Globule diameter	Globule weight
		g/sec	mm	g
D.C.	Positive	4·2	5–7	0·6–1·8
D.C.	Negative	5·8	3–4	0·15–0·35
A.C.		4·9	up to 2½	up to 0·08

These results show that d.c. electrode-positive arcs produce the largest globules and the lowest burn-off rate, d.c. electrode-negative arcs the intermediate-size globules and the highest burn-off rate, and a.c. the smallest globules and intermediate burn-off rate.

These experimental determinations can be explained in a satisfactory manner by considering the differences between the cathode spot and the anode area. The cathode is subjected to a very localized heat source of high intensity (120 kA/cm^2), and the anode is bathed, at least over the whole area of the tip, in a heat source of relatively low intensity (500–1 000 amp/cm^2). When the consumable electrode is positive on a d.c. supply there will generally be a zone of liquid metal over the whole anode area, and the transfer of heat from the arc to the solid portion of the electrode will take place through this liquid zone. The liquid will detach periodically in the form of large globules whose size will be related to the diameter of the electrode up to a certain critical diameter, and these will be the largest globules for the particular diameter of electrode. Since heat must be transferred through the liquid molybdenum, heating of the solid metal in the electrode is inefficient. Conditions when the consumable electrode is negative on a d.c. supply are very different. Heat is then supplied to the electrode by the high-intensity cathode spot, and very rapid localized melting takes place. The arc forces are so great that the molten metal is blasted away from the area as soon as it is formed, some probably detaching from the electrode immediately, but the majority collecting on the drip-point or points and becoming detached periodically. Thus the cathode spot can supply heat almost directly to the solid metal in the electrode during the whole course of the operation, and heat transfer is more efficient than when it is through a layer of molten metal. The size of globules formed will depend on the effective size of the irregular drip-points at which the molten metal collects, but will certainly be less than when the whole area of the electrode is acting as a single drip-point.

Microscopic examination of etched sections of electrode tips

have confirmed the difference in thickness of the liquid-metal zone in the two cases discussed.

When the arc is operated on an a.c. supply the sets of conditions discussed above will obtain for alternate half-cycles. From the arguments previously advanced an intermediate burn-off is to be expected and is found in practice, but a prediction of globule size cannot be made, since steady conditions on either polarity do not persist long enough for drip detachment by either of the mechanisms discussed to occur. As shown in Table 4, the globules are, in fact, considerably smaller than for either type of d.c. arc. This effect is thought to be due to the intermittent action during the negative half-cycle of arc forces on the molten metal formed during the positive half-cycle, these short-duration high-energy forces blasting the molten metal away from the electrode in the form of small particles. The flat shape of the electrode tip produced during a.c. melting was also to be expected under conditions where neither of the tips characteristic of d.c. operation can form.

(4) CONCLUSIONS

Conventional welding equipment is satisfactory as a power source for the arc-melting process using consumable molybdenum electrodes.

Experience, together with a study of the nature, shape and stability of a.c. and d.c. arcs at low gas pressures, has shown that the d.c. electrode-negative arc is the most suitable as regards ingot quality and mould life within the range of currents studied. To produce $1\frac{3}{4}$in-diameter molybdenum ingots from 1 cm-diameter electrodes, a current of 1–1·3 kA is required for the best results.

Detrimental spatter or vapour-initiated discharges can be minimized by correct plant design, including attention to such details as insulation, spatter guards and choice of materials.

Large differences exist between certain arc voltage, gas pressure and arc-length relationships for the d.c. positive, d.c. negative and a.c. molybdenum-depositing arcs.

The shape of burn-offs has been found to be related to the type of current supply used. A tentative theory has been suggested to explain this phenomenon, and in particular the systematic wandering of the cathode spot. Both clockwise and anti-clockwise rotations of the arc, at various velocities, have been observed.

For molybdenum-depositing arcs in vacuum, the d.c. electrode-positive arc produces the largest globules and lowest burn-off rates, the d.c. electrode-negative arc produces smaller globules but the highest burn-off rate, and the a.c. arc produces very small globules and an intermediate burn-off rate. An explanation of these phenomena has been given.

The foregoing discussion on the electrical aspects, coupled with practical experience and a survey of the metallurgical characteristics (described elsewhere[5]), has shown how satisfactory the consumable-electrode arc-melting process is, at least for molybdenum.

(5) ACKNOWLEDGMENTS

The work described was carried out in the Armament Research Establishment under the direction of Dr. L. Northcott, to whom the author is indebted. He also wishes to thank Mrs. J. E. Jones and Messrs. G. L. Hopkin and D. O. Pickman for helpful assistance and discussion during the course of the investigation and in preparation of the paper for publication. Acknowledgment is made to the Chief Scientist, Ministry of Supply, and to the Controller of H.M. Stationery Office, for permission to publish the paper.

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THE THEORY AND APPLICATION OF A SELF-PROPELLED STATOR-FED FREQUENCY CONVERTOR

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(*The paper was first received* 23*rd July, and in revised form* 18*th September*, 1954.)

SUMMARY

A variable-speed squirrel-cage motor has been a desirable aim since the general acceptance of a.c. supplies. The paper contains a description of a suitable and practically proved system of variable-frequency control for this and other purposes provided by a self-contained rotating frequency convertor, called the Speedmaster. The theory and application of this frequency convertor and some variants to a.c. variable-speed single- and multi-motor drives, utilizing different types of a.c. motors, are presented. Selected examples of actual equipments are included.

(1) LIST OF PRINCIPAL SYMBOLS

Convertor Quantities (referred to Rotor)

E_2 = Rotor standstill (open-circuit) voltage.
E_n = Rotor voltage at speed n.
E_s = Slip-ring voltage = Induction-motor stator voltage.
E_c = Commutator voltage.
E_{2R} = Total voltage introduced into rotor circuit.
I_2 = Rotor current.
I_s = Slip-ring current = Induction-motor stator current.
I_M = Reactive current.
f = Supply frequency.
F = Slip-ring frequency = Induction-motor stator frequency.
n_S = Synchronous speed.
n = Actual speed.
s = Slip.
r_1 = Stator resistance.
r_2 = Rotor resistance (as commutator machine).
r_a = Equivalent rotor resistance (as convertor).
r_r = External-rotor-circuit resistance (regulator and brush drop).
x_m = Total reactance (referred to f).
x_r = External-rotor-circuit reactance (referred to regulator).

Induction-Motor Quantities (referred to Stator)

I_μ = Magnetizing current.
I_∞ = Ideal short-circuit current.
N_S = Synchronous speed (referred to f).
N = Actual speed.
S = Slip (referred to F).
All quantities are in values per phase.

(2) INTRODUCTION

(2.1) The General Problem of Speed Control of Electrodynamic Machines

Broadly speaking, a commutator[1] is the element required in an electrodynamic machine to convert the frequency of the current of the stationary part into the frequency of the rotating part irrespective of the latter's rotational speed. Thus it is possible to introduce adjustable voltages of the frequency existing in the stationary part into the circuit of the rotating part for the purpose of speed adjustment, Ward Leonard sets and a.c. commutator motors being typical examples of this principle for constant-flux machines. In the former case the adjustable voltage is a direct voltage, i.e. of zero frequency, which, when applied to the commutator of the d.c. motor and coinciding with d.c. excitation of the stationary part, causes the machine to rotate at a speed where balance between e.m.f. and applied voltage is obtained; this determines the frequency of the alternating currents and voltages in the rotating part. With a stator-fed a.c. commutator motor[2] the adjustable voltage is obtained through a suitable variable-voltage transformer, e.g. an induction regulator, and this voltage of supply frequency is applied to the commutator, coinciding, of course, with the excitation of supply frequency of the stationary part. The value and direction of the adjustable voltage applied to the commutator determines the speed of the rotating part; the frequency of the alternating currents and voltages in that part being dependent on the difference between the synchronous speed of the rotating field excited from the stationary part, and the actual speed of the rotating part.

Speed variations through flux adjustment, i.e. field regulation, where a fixed voltage is applied to the rotor or armature, still require a commutator for the same reasons.

A different approach, obviating the necessity of a commutator for the speed adjustment of the motor, is to use an a.c. multiphase motor—in itself inherently a constant-speed machine—and to change or adjust the speed of its rotating field. The most common solution on these lines is, of course, the pole-change motor.

In order to achieve stepless speed adjustment of a.c. motors, a stepless variation of the supply frequency is required, resulting in a proportional variation of the speed of the rotating field.

(2.2) Steplessly-Variable Frequency Supplies

For the purpose of producing an adjustable frequency supply, alternators or slip-ring frequency-changers driven by variable-speed d.c. or a.c. motors have been suggested and used to some extent in practice. These solutions entail a double and even multiple conversion of energy, particularly if wide frequency ranges are required, with a consequent large aggregate of machinery and high inherent power losses.

The desirability of a compact, economical and readily controllable arrangement of high efficiency for the conversion of a fixed-frequency supply into one of variable frequency, adjustable over a wide range, has led to the development of a self-contained and self-propelling frequency convertor which has become known as the Speedmaster, the description, properties and theory of which are the main subject of the paper.

(2.3) Main Incentives for Speed Adjustment by Variable Frequency

Before describing the principle of the new frequency-convertor arrangement, it may be opportune to outline the reasons for, and practical importance of, variable-speed motors without commutators, in particular squirrel-cage a.c. induction motors.

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.
Dr. Schwarz is with Laurence, Scott and Electromotors, Ltd.

The case for the squirrel-cage motor as such needs no emphasis. But it will also be generally realized that its inherent property of being a fixed-speed motor on the one hand, and the endeavour to use it as a driving medium as widely as possible on the other hand, has resulted in a tendency to put up with the restriction of one or two fixed speeds and to introduce intricate arrangements for obtaining a larger number of speeds, or steplessly adjustable ones, by mechanical means. The over-emphasis laid on the desirability to use squirrel-cage motors has been reduced and mitigated to a steadily increasing degree by the use of variable-speed d.c. and a.c. motors, the latter having been successfully developed and extensively applied in the more recent past.

However, there is a large field of applications where commutators on the driving motor are undesirable, or in certain cases even objectionable, to an extent which makes their use impossible for practical purposes.

The commutators may create difficulties on drives where excessive extraneously created vibrations are unavoidable. The space requirement of any d.c. or a.c. commutator motor may be prohibitive, or the location of the machine such that maintenance of the commutator may be impossible or difficult. Where a comparatively large number of motors have to be simultaneously adjusted in speed, this may lead to undesirable maintenance requirements in view of the large number of individual commutators. The necessity for total enclosure owing to contaminated atmospheres, particularly of the explosion-proof kind, may create difficulties in the application of commutator machines of any type. Often the inertia of the rotating members of d.c. or a.c. commutator machines may be undesirable where quick acceleration, deceleration and reversal are required.

Conversely, the use of squirrel-cage motors supplied from a constant-frequency source, even with fixed operational speed, may be made difficult or even impossible because of frequent starting, reversing, plugging, etc., of heavy-inertia drives owing to the unavoidable losses incurred thereby, which are often impossible to dissipate from the machine, particularly with totally enclosed designs. Then starting and reversing at low frequencies, and accelerating and decelerating by frequency regulation, may overcome these difficulties and offer economical all-round solutions.

Combinations of the above-mentioned and other conditions often occur in practice, reinforcing the case for the described solutions.

The numerous applications mentioned throughout the paper are all examples of existing equipments, many of which have been in operation for several years. Thus, whilst the paper is largely concerned with the theoretical aspect of the self-propelled frequency convertor, there is already available a large volume of practical experience to support the conclusions reached and to prove the practical importance and utility of the frequency-convertor system. Broadly, the actual applications fall into two main groups—cases where other solutions are technically impossible or at least too involved to be advisable, and cases where economical considerations favour the Speedmaster from the point of view both of capital expenditure and operating costs including maintenance.

(3) GENERAL PRINCIPLE OF THE FREQUENCY-CONVERTOR SET

(3.1) Basic Arrangement

The basic arrangement[3] of the frequency convertor as applied to the speed adjustment of a.c. motors is shown in Fig. 1. It will be seen that the convertor has a multi-phase stator winding connected to a constant-frequency supply, and a commutator-type rotor winding with tappings connected to a set of slip rings. The commutator brushes are fed from the constant-frequency supply through a variable-voltage transformer which in the block schematic is shown as an induction regulator. The a.c. (induction) motors supplied have their stator windings connected to the variable-frequency supply obtained from the slip rings of the Speedmaster.

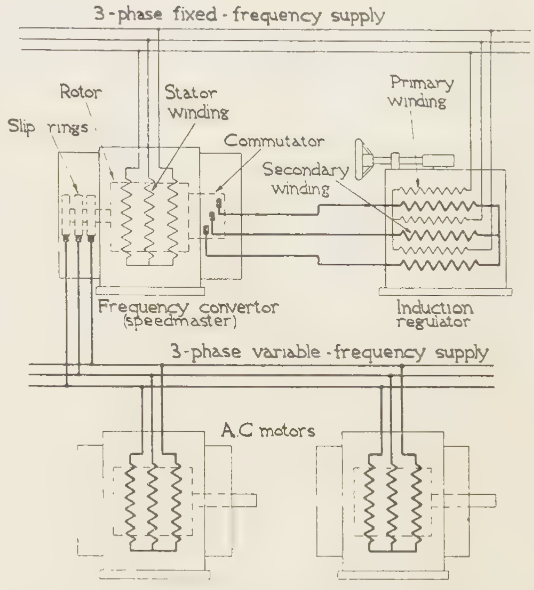


Fig. 1.—Block schematic of basic arrangement of frequency-convertor set with a.c. motor load.

(3.2) Operation without Load

Considering first the operation with the induction motors disconnected from the slip rings, the frequency convertor behaves exactly as an idle-running shunt commutator motor with induction-regulator control.[2]

The commutator converts the applied voltage of supply frequency f into a voltage of slip frequency F. As the tappings in the rotor winding (see Fig. 3) rotate with the rotor, the voltage E_s measured at the slip rings is, apart from secondary effects, identical in magnitude with the voltage E_c applied to the commutator brushes, but the frequency, F, of the voltage E_s is that of the rotor winding, i.e. it is proportional to the difference between the synchronous and the actual speed of the convertor. This can be expressed by the following two equations:

$$E_s = E_c = E_2(n_S - n)/n_S \quad . \quad . \quad . \quad . \quad (1)$$

$$F = f(n_S - n)/n_S \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Fig. 2 shows the voltage and frequencies as a function of the speed of the convertor.

(3.3) Operation of Frequency Convertor feeding A.C. Motors

If the voltage obtained at the slip rings of the convertor is fed into the stator winding of an induction (or synchronous) motor, the speed of the rotating field and the applied voltage will change in accordance with the proportional frequency (see Fig. 2), resulting in a proportional speed change of the motor, its flux remaining constant apart from secondary effects. The a.c. motors are therefore capable of supplying a constant torque over the whole speed and frequency range. Modifications of the torque-loading capacity of the a.c. motors at different speeds are the subject of later Sections.

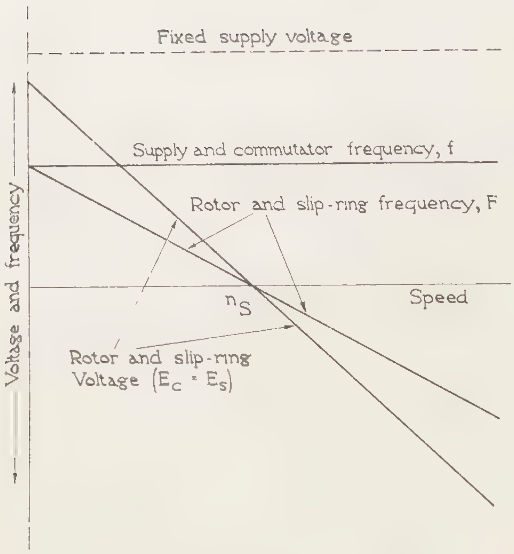


Fig. 2.—Voltage and frequency variation at commutator and slip rings.
The ratio of slip-ring voltage to slip-ring frequency E_S/F is constant.
n_s = Synchronous speed.

Reverting again to Fig. 2, it will be clear that an induction or other a.c. motor connected to the slip rings remains at standstill if the convertor is operated at its synchronous speed n_S, since under this operating condition the frequency and voltage at its slip rings are zero.

If, through an adjustment of the induction regulator, the voltage applied to the commutator brushes is increased so as to obtain sub-synchronous operation of the Speedmaster, the speed of the induction motor is increased in proportion to the increasing frequency.

With an adjustment of the convertor speed in the super-synchronous range, the phase rotation of the slip-ring voltage changes, and the induction motors run in the reverse direction, their speed again increasing with increasing difference between the synchronous and the actual speed of the convertor. The "negative" frequency so obtained agrees with eqn. (2) and Fig. 2 and therefore signifies the opposite phase rotation of the slip-ring voltage.

Assuming the synchronous speed of the Speedmaster and a.c. motor to be the same, and neglecting the slip, if any, of the latter, it is evident that the sum of the convertor and motor speeds must always equal the synchronous speed,

i.e. $$n + N = n_S = N_S \quad . \quad . \quad . \quad . \quad . \quad (3)$$

or generally for a motor synchronous speed, N_S, differing from n_S,

$$n + N(n_S/N_S) = n_S \quad . \quad . \quad . \quad . \quad . \quad (3a)$$

In the basic arrangement of Fig. 1 the power required for the a.c. induction motors is supplied through the induction regulator to the convertor commutator, passing through the rotor winding to the slip rings to be fed into the stator windings of the motors. The stator winding of the frequency convertor carries only reactive currents apart from the small active current required to cover the iron, friction, windage and part of the copper losses of the convertor.

There can be no energy transfer of a major order under steady-state conditions from the stator to the rotor. Only with speed changes is the energy required for the acceleration or deceleration of the convertor rotor transmitted through its air-gap (see Section 9.2.3).

(4) THE FREQUENCY-CONVERTOR ROTOR WINDING

(4.1) Basic Connections

It is known from the theory of the rotary convertor that the choice of the number of slip rings and tappings of the armature winding has a substantial influence on the copper losses.[4] Whereas with the rotary convertor the number of brush arms is naturally limited to two per pair of poles, there is no such limitation with the frequency convertor, and the choice is conditioned by design considerations only, regarding the commutator, brush-gear and the number of phases which can be conveniently accommodated in the transformer or regulator feeding the commutator brushes.

It will be seen at once that increasing the number of brush arms per pole, as well as increasing the number of slip-ring tappings, reduces the copper losses due to the current passing through the rotor winding. Moreover, the design of the commutator is influenced by the number of brush arms per pole. As with a given commutator and number of poles the maximum commutator voltage is limited by the permissible voltage between adjacent commutator bars, a larger number of brush arms per pole reduces the current to be carried by each line of brushes and results in a shorter commutator.

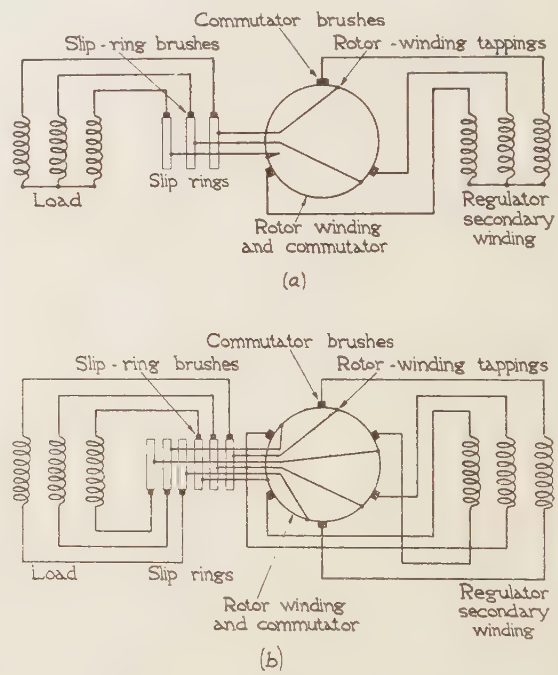


Fig. 3.—Rotor-connection diagrams of frequency-convertor set.
(*a*) 3/3-phase rotor.
(*b*) 6/6-phase rotor.

Fig. 3 shows two of the combinations in practical use for a 2-pole convertor. The 3/3-phase connection of Fig. 3(*a*) is obtained by feeding the commutator through three brush arms from a star- or delta-connected winding, whilst three tappings and slip rings are provided for the supply of the variable frequency into the star- or delta-connected primary winding of one or more a.c. motors.

By using three open phases on the commutator side [see Fig. 3(*b*)], and providing six tappings and slip rings basically to feed three open phases on the output side of the convertor, a 6/6-phase system in the armature is obtained, with consequent considerable reduction of the effective armature current and copper losses. The 6-slip-ring arrangement can alternatively be utilized to give two 3-phase variable-frequency supplies for a

number of star- or delta-connected motors divided into two approximately equal groups. The 6/6-phase system does not require any deviation from normal 3-phase windings on the input and output side, and is therefore most convenient from every point of view as an overall solution for a wide range of convertors.

Of course, it is also possible to use a 6/3- or a 3/6-phase system, resulting in intermediate values of effective current and copper losses in the rotor winding. In principle, any number of phases and combinations can be used, and, moreover, it is usual to increase the number of phases with increasing size of machine in accordance with obvious design, economic and efficiency considerations.

(4.2) Current Distribution in the Rotor Winding

In order to obtain a clear picture of the mechanism of frequency conversion, and in this way of the actual current distribution, the rotor winding of Fig. 3(*b*) is shown in Fig. 4(*a*) as a circle. This

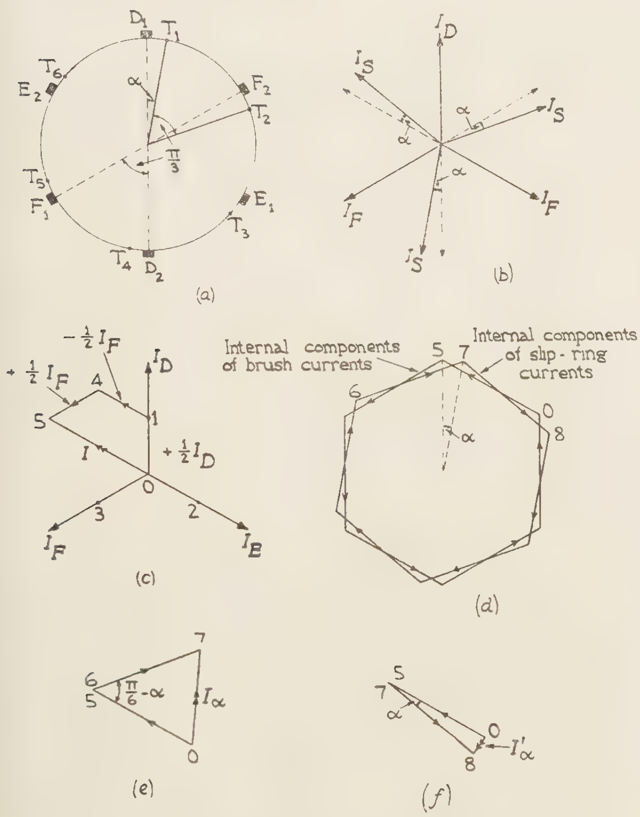


Fig. 4.—Current distribution in 6/6-phase rotor.

(*a*) Relative positions of brushes and tappings for rotor position α.
(*b*) External current vector diagram.
(*c*) Determination of internal commutator current (for $m = 6$).
(*d*) Internal brush and slip-ring current vector polygons for rotor position α.
(*e*) Coil current I_α in section D_1T_1 for rotor position α.
(*f*) Coil current I'_α in section T_1F_1 for rotor position α.

can be considered at the same time as the periphery of a 2-pole rotor and a commutator with six equally-spaced brushes D_1, F_2, etc. The six tappings T_1, T_2, etc., for the slip rings are shown displaced by an angle α against the brushes.

The angle α depends on the physical position of the rotor relative to the fixed brushes. In the rotor position $\alpha = 0$ the tappings concide with the brushes; the current entering the rotor from the brushes does not flow through the rotor winding but goes directly to the slip-ring tappings. This is strictly true only with tappings arranged on the commutator side of the rotor winding, but it is for practical purposes correct if the tappings are on the other side of the rotor, since only one conductor of the rotor winding will then carry current.

The vector diagram [Fig. 4(*b*)] shows the external current vectors for the rotor position α; I_D, I_E, I_F and I_S being respectively the vectors of the external commutator and slip-ring currents, the former being suffixed *D*, *E* and *F* corresponding to the three open rotor phases. For the displacement angle $\alpha = 0$, the vectors of the currents I_S take the position shown dotted, signifying that they are equal and opposite to the commutator currents.

In the first place, it is necessary to determine the vectors of the internal currents I, under the assumption that only the commutator is fed. Each external phase current I_D, I_E, I_F is split into two halves which are represented by the vectors 01, 02, 03 [see Fig. 4(*c*)] for the currents entering the commutator through the brushes D_1, E_1, and F_1, respectively. The positive direction of these three vectors is assumed to refer to the flow of currents in the clockwise direction in Fig. 4(*a*). With this assumption, the current entering the brush E_1 and flowing to E_2 in the anticlockwise direction can be represented by the vector 14, which is equal in magnitude and opposite in direction to 02. Choosing the winding section D_1F_2 of Fig. 4(*a*) as the basis of Fig. 4(*c*), the current vector 14 has to be added to 01. The current entering the winding at F_1 flows through the chosen section in the clockwise direction and can therefore be represented by the vector 45, which is equal to 03. The current I in the winding section D_1F_2 is the vectorial sum 05 of the three currents 01, 14 and 45, and is equal in magnitude to the external current I_D but displaced from it by 60°. The vectors of the six internal component currents in the six identical sections of the winding between brushes can therefore be represented by the hexagon of Fig. 4(*d*).

Similarly, the vectors of the internal components of the slip-ring currents I_S form an identical hexagon with the opposite vector directions displaced by α, as also shown in Fig. 4(*d*).

For the same rotor position α, Fig. 4(*e*) shows the vectorial addition of the internal components of the brush and slip-ring currents 05 and 67 respectively, the resulting current I_α being 07 in the part of the winding D_1T_1. Similarly, in the winding section T_1F_2 the internal slip-ring current 78 [Fig. 4(*f*)] is vectorially added to the internal commutator current 05, resulting in the vector sum 08 representing the vector of the actual current I'_α.

It will be seen that the maximum effective current carried by any part of the rotor winding occurs when α approaches 0° and all multiples of 60°; it is then equal to the external commutator or slip-ring current. However, the part of the winding so loaded is only next to the tappings when these are close to the brushes. At any other time and in any other part of the winding the current is less, being reduced in the whole winding to zero in the position where the tappings coincide with the brush position.

As none of these considerations depends on the speed of rotation of the rotor, but only on the relative local position of the tappings as referred to the brushes, the voltages, currents, copper losses and resulting apparent resistance of the rotor winding to the passage of current from the commutator to the slip rings can be treated mathematically in a simple way, as shown in Section 15.

In Fig. 5 the resulting currents flowing in the coils adjacent to the slip-ring tappings, and in a typical coil halfway between two tappings, are shown as a function of the displacement angle α, which, assuming the rotational speed of the rotor to be constant, also signifies time. The cycle is, of course, repeated every time the tapping passes a brush position.

(4.3) Rotor Copper Losses

In order to obtain a complete picture of all relevant data, Table 1 has been compiled for different numbers of phases on the commutator and slip-ring side. All currents and losses are,

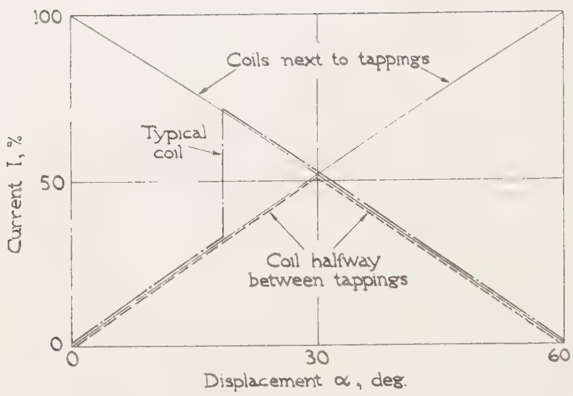


Fig. 5.—Current loading of coils in 6/6-phase rotor.

thus facilitating the theoretical treatment of the behaviour of the machine by vector diagrams or analytically.

(*c*) The effect on the commutation of the m.m.f.'s produced by the resultant currents which give rise to local fluxes becomes a problem of the first importance. These local fluxes produce a transformer voltage in the coils short-circuited by the brushes during commutation in the same way as the main flux. This problem only exists to a lesser extent in commutator motors so far as the harmonic content of the main flux is concerned. It is therefore clear that only rotor windings which are capable of dealing adequately with such harmonics[5] can be successfully employed for such frequency convertors. The detailed treatment of rotor windings in the light of this commutation problem, and also in connection with the possibilities of, and requirements for, the correct arrangements of the tappings for the slip rings, is, however, outside the scope of the paper.

Table 1

Currents, Voltages and Losses of Convertor Rotors

Commutator phases	3	6	6	12	12
Slip-ring phases	3	3	6	6	12
Commutator voltage*	$0{\cdot}866E$	E	E	E	E
Commutator current	$2I$	I	I	$0{\cdot}5I$	$0{\cdot}5I$
Slip-ring voltage	$0{\cdot}866E$	$0{\cdot}866E$	E	E	E
Slip-ring current	$2I$	$2I$	I	I	$0{\cdot}5I$
Internal current as commutator machine	$1{\cdot}155I$	I	I	$0{\cdot}966I$	$0{\cdot}966I$
Maximum internal coil current, I_α, as convertor	$2I$	$1{\cdot}53I$	I	$0{\cdot}752I$	$0{\cdot}5I$
Losses as commutator machine	$1{\cdot}33RI^2$	RI^2	RI^2	$0{\cdot}933RI^2$	$0{\cdot}933RI^2$
Losses as convertor†	$0{\cdot}844RI^2$	$0{\cdot}51RI^2$	$0{\cdot}176RI^2$	$0{\cdot}114RI^2$	$0{\cdot}0466RI^2$
Ratio of convertor to commutator-machine resistance r_a/r_2	$0{\cdot}63$	$0{\cdot}51$	$0{\cdot}176$	$0{\cdot}122$	$0{\cdot}050$

* E = Diametrical voltage.
† Losses remain unchanged if the number of phases on the commutator and slip-ring sides are interchanged.

for the sake of comparison, referred to the current and losses of 6-phase commutator feeding, for which the internal winding current and the external brush current in one phase are equal (see Section 4.2) and designated by I. The effective resistances are referred to the total resistance, R, of the winding in series, making the losses RI^2 for this case. It is, moreover, assumed that the total slip-ring output for all connections is the same in terms of apparent power.

It will be seen from Table 1 that an increase in the number of phases, whether on the slip-ring or commutator side, results in reduced overall losses and in reduced maximum local currents next to the tappings.

(4.4) Conclusions

(*a*) Under conditions of equal input and output the rotor winding of the frequency convertor does not produce an m.m.f. corresponding to the number of pole pairs of the winding. If the actual m.m.f. distribution obtained is resolved into its harmonic content, the result can only consist of m.m.f.'s of higher order.

(*b*) As a consequence of (*a*), there is no need to consider the copper losses and other effects of currents of the first order, which may flow in the rotor winding and which will be considered later, in any other way than as being independent of, and superimposed on, the resulting currents of higher order. The copper losses can be obtained simply by adding the losses of the first- and higher-order currents. In agreement with this, two different resistances, r_2 and r_a, can be established for the rotor winding,

(5) THE BASIC VECTOR DIAGRAM

(5.1) Operation without Slip-Ring Current

The light-running frequency convertor, i.e. with open external slip-ring circuit, behaves in the same way as the stator-fed shunt a.c. commutator motor under no load. As it has been treated elsewhere,[2] it will not be necessary to deal with this condition in detail. The only practical difference is that the leading compensating voltage component introduced as a rule in the rotor circuit of the a.c. shunt commutator motor is not necessarily employed with the frequency convertor. Compensating voltages, if utilized, are usually small compared with those of shunt commutator machines, and no measures are therefore required to limit the light-running magnetizing currents.

(5.2) Operation with Active and Reactive Loads

As the Speedmaster does not supply any mechanical output at its shaft, the only active current in its rotor winding is that required to cover the friction, windage and certain stray losses of the machine (see Section 3.3). Thus there is no active current of the first order in the rotor under any loading conditions, or expressed differently, the active components of the slip-ring and commutator currents must balance each other, so that for these currents the results described in Section 4 on m.m.f. distribution and rotor copper losses are fully applicable.

The position of the reactive components of the slip-ring and commutator currents is fundamentally different, since it is possible for a reactive current flowing in the stator winding to produce a

balancing m.m.f. for a resulting reactive current of fundamental frequency flowing in the rotor winding. It is therefore necessary to investigate, in the first place, the conditions arising from a reactive load taken from the slip rings of the frequency convertor.

(5.3) Voltage and Current Vector Diagram for Reactive Load

A virtually reactive load may be represented by light-running induction motors connected to the slip rings of the convertor. In Fig. 6 the voltage and current vector diagram, referred to the rotor circuit of the frequency convertor, is drawn for such an inductive load.

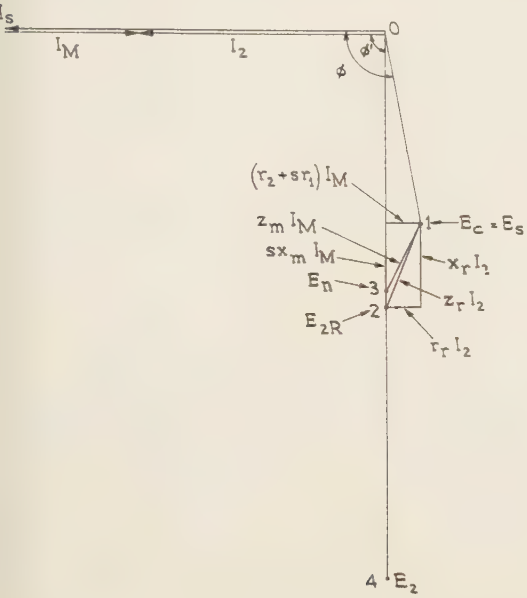


Fig. 6.—Voltage and current vector diagram for reactive load.

The vector I_s of the slip-ring current should, under this assumption, be displaced by $\phi = 90°$ against the slip-ring voltage E_s, but in order to simplify the treatment, it is proposed to use the term "reactive current" with reference to the e.m.f. of the convertor, so that in Fig. 6 I_s is drawn at right-angles to $E_2(\phi' = 90°)$. All vectors are referred to the supply frequency f, as is usual in the treatment of induction machines. The slip-ring voltage E_s is, for the purpose of the vector diagram, assumed to be identical with the commutator voltage E_c. In fact, these voltages differ owing to the rotor-voltage drop of the resultant currents dealt with in Section 4. This voltage drop $r_a I_s$ is of a minor order and does not contain a component of fundamental frequency.

The diagram is drawn for the brushes in the "neutral" position, in which the open-circuit voltage, E_2, of the rotor has the same phase position as the secondary open-circuit voltage, E_{2R}, of the regulator.

The current I_2 in the rotor circuit, which flows through the commutator brushes and hence through the regulator, is the vectorial sum of the reactive rotor current I_M and the slip-ring current I_s. The vectorial addition is the mathematical expression of the fact that the m.m.f. balance between the reactive slip-ring and commutator currents is supplied by the reactive current I_M.

It will be readily seen from the vector diagram (Fig. 6) that the necessary condition for the balance of the voltages is fulfilled as the vector sum of the open-circuit voltage E_{2R}(02) of the regulator, at its chosen adjustment, and the voltage drops in the regulator circuit 21—which for the purpose of this diagram also include the voltage drop at the brushes—balances the commutator voltage E_c(01).

It is, moreover, necessary that the vectorial sum E_n(03) of the commutator voltage E_c(01) and the voltage drops 13 of the reactive current I_M must have the same phase position as the open-circuit voltage E_2(04), which therefore, under all operating conditions, is the locus of the vector ends of E_n. The ratio between the voltage E_n (which is the effective e.m.f. in the rotor winding) and the open-circuit voltage E_2 represents the slip s of the frequency convertor:

$$s = (n_s - n)/n_s = E_n/E_2 \quad . \quad . \quad . \quad . \quad (4)$$

Eqn. (4) becomes identical with eqn. (1) for the ideal no-load case, i.e. with no current in the secondary circuit, when the rotor voltage E_n is equal to the regulator voltage E_{2R} applied to the brushes.

(5.4) General Load Case

In the vector diagram of Fig. 7 the slip-ring current I_s is shown lagging behind the slip-ring voltage E_s by an angle ϕ and behind

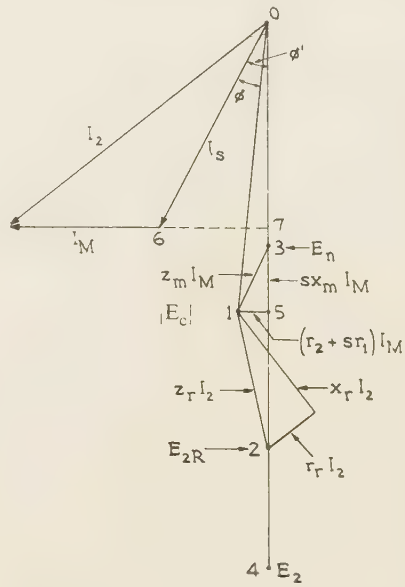


Fig. 7.—Voltage and current vector diagram for general load case.

the e.m.f. E_n of the frequency convertor by ϕ'. This is the general load case represented, for instance, by an induction motor fed from the slip rings of the Speedmaster running at a sub-synchronous speed, i.e. with a positive slip according to eqn. (4).

Here again, the vectorial sum of the slip-ring current I_s and the reactive current I_M at right-angles to the e.m.f., E_n, is equal to the rotor current I_2 flowing through the secondary circuit of the regulator and the commutator brushes.

Consequently, the vectorial sum of the adjusted open-circuit secondary voltage E_{2R}(02) of the regulator and the voltage drops 12 produced by I_2 in that circuit gives the commutator voltage E_c(01) which is identical with E_s (see Section 5.3).

The voltage drop 13 produced by the reactive current I_M in the convertor added vectorially to the commutator voltage E_c(01) equals the e.m.f. E_n(03), eqn. (4) again being applicable.

These conditions can also be expressed by the following vectorial equations:

$$\mathbf{I_s} + \mathbf{I_M} = \mathbf{I_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

$$\mathbf{E_{2R}} + z_r\mathbf{I_2} = \mathbf{E_c} = \mathbf{E_s} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

$$\mathbf{E_c} + z_M\mathbf{I_M} = \mathbf{E_n} \quad . \quad . \quad . \quad . \quad . \quad (7)$$

Eqns. (5), (6) and (7) are generally applicable to all loading conditions of the frequency convertor.

The adjusted open-circuit regulator voltage E_{2R} can also contain a leading or lagging component at right-angles to E_2 without changing the principle of the vector diagram of Fig. 7 (see Sections 5.5 and 6.4). A compensating voltage can be introduced by brush adjustment, resulting in a displacement angle between E_n and E_{2R}, or by any of the means applying to shunt commutator machines.[2]

(5.5) Conclusions

It will be seen that the reactive current I_M in the convertor rotor winding is of great importance for the behaviour of the machines in several respects. Reference has already been made to the fact that this current has to be treated in the same way as a current in a shunt commutator machine with regard to losses in the rotor winding (see Section 4.4). In the stator winding, the reactive current equivalent to I_M adds to, or subtracts from, the magnetizing current of the convertor.

The current I_M, moreover, influences the actual speed and therefore the output frequency of the convertor, as can be immediately seen from the vector diagrams (Figs. 6 and 7), the reactive voltage drop of I_M having a speed-decreasing effect with a purely reactive load as in Fig. 6 and a speed-increasing effect with the essentially active, slightly lagging, load condition represented by Fig. 7. The influence on the convertor speed produced by I_M combines, of course, with the effect of the voltage drops of the rotor current I_2 produced in the induction regulator. Apart from the influence of I_M on the actual operational speed of the convertor, it also influences the magnitude of the output voltage.

The ratio E_s/F (volts per cycle) is of particular importance for the operational behaviour of a.c. motors supplied from the convertor slip rings, as this determines their flux, overload capacity, magnetizing current, starting torque, etc. Conversely, the characteristic properties of the load, e.g. the a.c. motor or motors, will affect the behaviour of the convertor. The problem of design of the combination has therefore to be approached as a whole (see Section 6).

Another important influence of the reactive current, I_M, which is clearly shown in the vector diagrams Figs. 6 and 7, is its effect on the rotor current I_2, which is the commutator current and also determines the loading of the commutator and its brush system. With the inductive reactive load (see Fig. 6) I_M reduces the commutator current I_2 in relation to the slip-ring current I_s, whereas with the essentially active load in Fig. 7, the reverse is the case.

At a phase displacement of ϕ' for which

$$\tan \phi' = x_r/r_r \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

I_s and I_2 coincide, i.e. the reactive current I_M passes through zero, which also signifies the point of minimum copper losses in the rotor winding for a given active load current.

The operational rotor losses and the other considerations enumerated in this Section, especially commutator loading, frequency and output-voltage variations at different loads, are factors that have to be considered in connection with the desirability or otherwise of introducing compensating voltages into the rotor circuit.

Broadly speaking, a lagging compensating voltage reduces I_M in Fig. 7; this may mean a negative, i.e. lagging, value of I_M for a given active load. The frequency regulation for varying load is consequently reduced, whilst at the same time the commutator current decreases in magnitude with increasing lagging compensating voltage, until it becomes purely active. A further increase of the lagging compensating voltage causes a lagging and increasing commutator current. Conversely, a leadin compensating voltage increases the frequency regulation an the commutator current for a given load, resulting, however, in better power factor of the set as a whole.

(6) ANALYTICAL AND GRAPHICAL TREATMENT

(6.1) Analytical Treatment of General Load Case

The analytical treatment is based on the vector eqns. (5), (6 and (7) derived from Fig. 7. The following equations can thu be established:

$$E_{2R} = sE_2 + sx_mI_M + r_rI_P + x_r(I_Q + I_M) \quad . \quad (9$$

$$(r_2 + sr_1)I_M = x_rI_P - r_r(I_Q + I_M) \quad . \quad . \quad . \quad (10$$

wherein I_P(07) is the in-phase and I_Q(67) the quadrature com ponent of I_s.

(6.2) Induction Motor as Load

Assuming the load connected to the slip rings of the converto to be an a.c. induction motor, its characteristic equation (circl diagram) has the form

$$(I_P - \alpha_sE_s)^2 + (I_Q - \beta_sE_s)^2 = (\gamma_sE_s)^2 \quad . \quad . \quad (11$$

α_s, β_s and γ_s being the constants of the motor at frequency $F = sf$ Eqns. (9), (10) and (11) determine the performance of the com plete set. There are four variables in these equations, namel s, I_M, I_P and I_Q, assuming, of course, a fixed adjustment of the induction regulator, i.e. a constant secondary voltage E_{2R}. B eliminating I_M and I_Q and neglecting the influence of the slip-rin frequency variation on the reactance of the induction motor which is permissible since these frequency variations are onl comparatively small with a fixed value of E_{2R}, an equation o the form

$$s^4 + (A_1I_P + A_2)s^3 + (A_3I_P{}^2 + A_4I_P + A_5)s^2 + (A_6I_P^2 + A_7I_P + A_8)s + (A_9I_P^2 + A_{10}I_P + A_{11}) = 0 \quad . \quad . \quad . \quad . \quad (12$$

is obtained. This equation represents the fundamental connec tion between the slip-ring frequency $F = sf$ and the active curren I_P of the induction motor for a given value of E_{2R}. In principl it is possible to obtain the complete performance of the set b calculating the curves from eqn. (12) for different regulato adjustments E_{2R}; this term enters into the constants A_1–A_{11}.

Another somewhat simpler approach is to assume values of and to determine the functional connection between I_P and E_{2R} which has the form of an ellipse:

$$E_{2R}^2 + B_1I_PE_{2R} + B_2I_P^2 + B_3E_{2R} + B_4I_P + B_5 = 0 \quad . \quad (13$$

B_1–B_5 being constants for a given value of s.

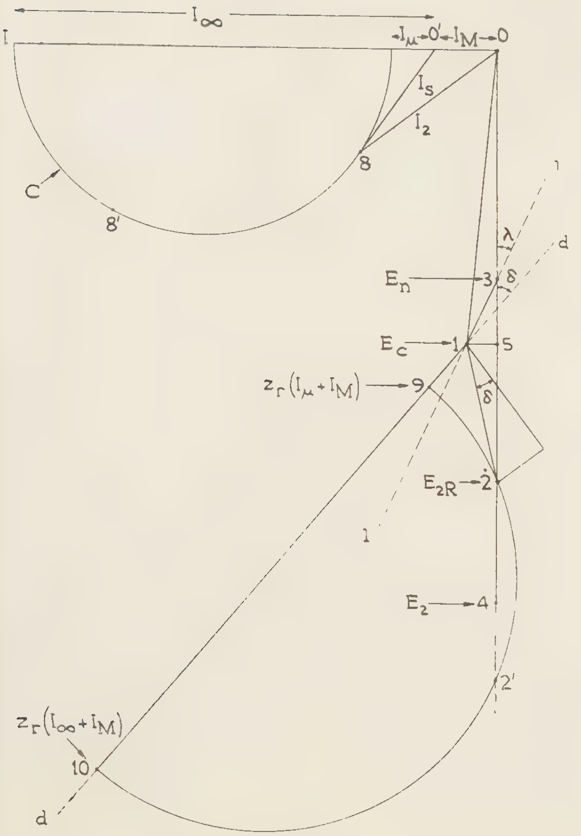
(6.3) Simplified Graphical Treatment

In view of the rather complicated nature of the equations i the preceding Section, a simpler approach has been evolved The graphical method used is illustrated in Fig. 8, which i based on the vector diagram of Fig. 7.

Assuming E_n(03) to be constant, i.e. a constant slip s and constant slip-ring frequency F, the locus of the vector ends 1 o $E_c(E_s)$ for variable values of I_M is a straight line ll defined by

$$\tan \lambda = (r_2 + sr_1)/sx_m \quad . \quad . \quad . \quad . \quad (14$$

Any chosen value of I_M determines a corresponding value o E_c, since 31 is the vector of the voltage drop of I_M in the con vertor. With F fixed and a value of I_M chosen, E_c is determine



ig. 8.—Graphical construction of voltage and current vector diagrams for frequency convertor with induction-motor load.

nd the constants of the induction motor are also fixed, and its haracteristics can be expressed by the circle diagram C with the rigin O′, displaced by I_M from O. I_μ is the magnetizing current nd I_∞ the ideal short-circuit current (of the original Heyland iagram) for the induction motor.

For any point 8 of the circle diagram C, the stator current of ie induction motor is $I_s(08)$, which at the same time is the slip-ng current of the convertor. The vector 08 represents the ommutator current I_2, as a comparison with Fig. 7 will imme-iately show.

The locus of the voltage drops $z_rI_2(12)$ is represented by the rcle C′ in Fig. 8, which is similar (geometrically) to the circle with an origin 1 corresponding to O. The diameter of C′ lies n the straight line *dd* drawn through 1 at an angle δ with 04 efined by

$$\tan \delta = r_r/x_r \qquad (15)$$

e scale factor being z_r.

Vector 19 is then the voltage drop $z_r(I_\mu + I_M)$ of the mag-etizing current I_μ of the induction motor plus the reactive otor current I_M of the convertor; and vector 1–10 is the voltage rop $z_r(I_\infty + I_M)$ of the ideal short-circuit current I_∞ of the duction motor plus the reactive rotor current I_M of the nvertor.

Since the locus of E_{2R} coincides with 04 (assuming that no mpensating voltage is used), the intersections 2 and 2′ of the rcle C′ and 04 are the two possible vector ends of E_{2R} fulfilling e condition of the assumed value of I_M.

These conditions are represented by equivalent points 8 and 8′ n the circle C of the induction motor. In other words, for the osen value of I_M there are, in principle, two possible operating conditions of the whole set with the slip-ring currents 0′8 and 0′8′ respectively.

By making different assumptions with regard to I_M, resulting in different positions of the point 1 on the locus *ll* and of the origin 0′, any number of solutions can similarly be easily found for a given value of *s* and therefore *F*. Each pair of points only requires the construction of the circles C and C′ as the respective loci for the vector ends of the currents and secondary voltage drops respectively. The whole process is repeated for different assumed values of the slip *s* and *F*, expressed by different values of $E_n(03)$, to obtain the complete performance of the set.

(6.4) Typical Performance with Induction Motor

Fig. 9 shows typical calculated torque/speed characteristics, drawn for different constant induction-regulator positions, for

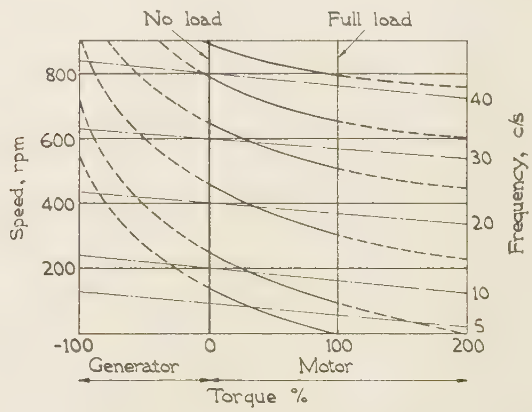


Fig. 9.—Torque/speed curves (for various regulator adjustments) of a 60h.p. 6-pole 40c/s motor supplied by a 50kVA 40c/s (max) convertor.

The above calculated torque/speed curves have been subtstantiated by tests.
– – – – – Lines of constant frequency.

an induction motor fed from a Speedmaster over a frequency range 0–40c/s. The actual operating range on the motor side between no load and full load is drawn in solid lines with dotted extensions for overload and regenerative conditions. The characteristics are based on zero compensation. It will be clear (see Section 5.5) that the behaviour of the set can be influenced by the adjustment of the compensation, by which means either the overload-capacity motoring and/or generating can be influ-enced. A magnetizing compensating voltage is required to obtain a wide range of regeneration, and a demagnetizing com-pensating voltage increases the motoring torque for any given adjustment of the induction regulator. The compensating voltage can be varied automatically in accordance with the load demand of the induction motor.

Furthermore, in Fig. 9 lines of constant frequency are shown dotted. The characteristics have been substantiated by test.

(6.5) Performance with Other A.C. Motors

The treatment of the set with a synchronous motor in place of an induction motor is similar and actually simpler, in view of the constant speed of such a machine for a given frequency, whilst the circle diagram remains in essence the same, with the proviso that the actual d.c. excitation has to be considered.

Generally speaking, any kind of load, and therefore any type of motor, can be treated graphically or analytically, by considering its actual characteristics. Amongst the practical applications are shunt and series characteristic commutator motors and mixed

systems containing different kinds of motors supplied with variable frequency from a Speedmaster (see also Section 10).

(7) GENERAL CONCLUSIONS AND DESIGN CONSIDERATIONS

As has been seen from the preceding Sections, the load current of an induction motor has two effects, firstly the slip produced in the induction-motor rotor for a given supply frequency and voltage in its stator, and secondly the influence of that load current on the operational speed and rotor frequency of the convertor for a given regulator adjustment.

The inherent rotor copper losses of the induction motor can be comparatively low without impairing the starting torque, and without in general necessitating any current-displacement rotor-winding construction, high starting torques being easily obtained with plain squirrel-cage motors. This is due to the start taking place with very low supply frequencies, with the consequent advantage of a relatively large effect of the rotor resistance as compared with that of the machine reactance. The current from the supply for a given starting torque is very low in view of the frequency and voltage ratio between the supply and induction-motor circuit. Starting torques of twice full-load and more can generally be obtained without exceeding the full-load running current of the set at maximum speed.

The influence of the stator resistance of the induction motor is, however, of the first order with low-frequency operation, and has therefore to be considered accordingly (see also Section 8.2).

With a system containing a synchronous motor, its speed depends, of course, only on the slip-ring frequency, but the shape of the torque/speed characteristic remains similar, as indicated in the preceding Sections. An interesting feature is that considerable starting torques can be obtained with a synchronous machine by applying the d.c. excitation at standstill and increasing the frequency from zero upwards at such a rate that the synchronous machine keeps in step.

(8) SYSTEMS OF SPEED REGULATION AND INDUCTION REGULATORS

Although in principle the same systems of speed regulation by rotor- and stator-voltage adjustment can be used as for shunt commutator machines,[2] the applications of these systems must be viewed in a different light when applied to the frequency convertor.

(8.1) Rotor-Voltage Regulation

The basic arrangement, as shown in the block schematic of Fig. 1, using a double induction regulator, produces a speed range of the frequency convertor symmetrical about the synchronous speed, resulting in a given frequency at the slip rings being obtainable twice, i.e. with a sub-synchronous and super-synchronous speed of the convertor.

There are circumstances in which this feature can be utilized. As a rule, however, the arrangement shown in Fig. 10 is preferable, in which a fixed "downward" voltage component E_A [see Fig. 10(*b*)] is introduced into the rotor circuit by an auxiliary stator winding [see Fig. 10(*a*)] in series with the secondary windings of the double induction regulator. The voltage component E_A is advantageously chosen to produce the secondary voltage approximately required for the middle of the speed range, with the result that the maximum induction regulator voltage E_{2Rmax} can be used in the positive and negative direction, in order to obtain the maximum and minimum resulting rotor voltages E_{nmax} and E_{nmin} for the required frequency range. The size of the induction regulator irrespective of its system is thereby reduced to less than half that required to obtain the rotor voltage without the use of the auxiliary winding.

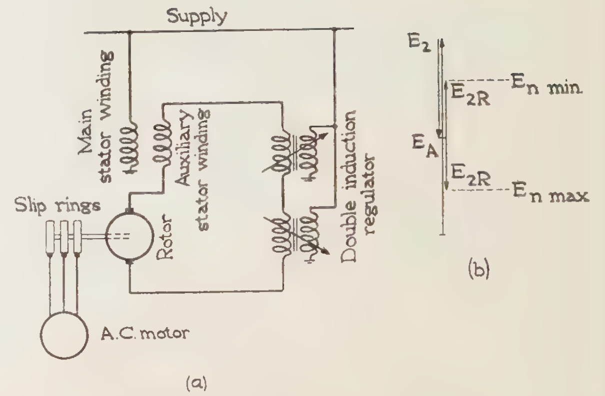


Fig. 10.—System using a double induction regulator and auxiliary stator winding.

In this and subsequent Figures only one primary and secondary phase is show i.e. two brush arms per phase, resulting in 6-phase feeding of the commutator windir

The energy transfer from the supply to the commutator circu then takes place to a large extent through the stator of tl frequency convertor, which acts as a transformer. As tl m.m.f.'s of the two stator windings are balanced there is n change in the principle outlined above (see Section 3.2), i.e. n energy transfer takes place through the air-gap of the converto

The same principle applied to the single induction regulato described in the author's earlier paper[2] results in the arrangemei shown in Fig. 11(*a*), the function of which will become clear fro

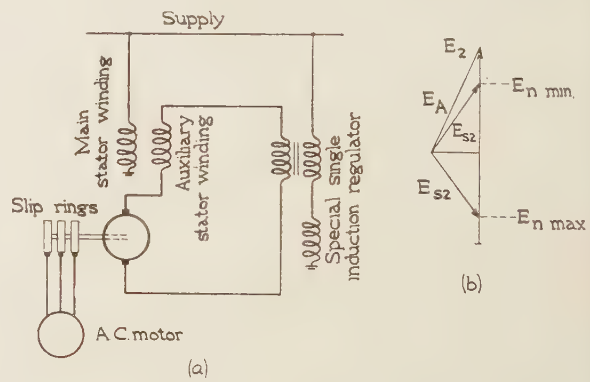


Fig. 11.—System using a special single induction regulator and auxiliary stator winding.

the vector diagram of Fig. 11(*b*). The voltage vector E_A of th auxiliary stator winding is then shifted against E_2. The maxi mum and minimum position of the regulator secondary voltag E_{s2} for the displacement angles $\pm 90°$ are shown in the vecto diagram. The locus of the vector ends of the resulting voltag E_{2R} coincides with E_2, since no compensating voltage is used.

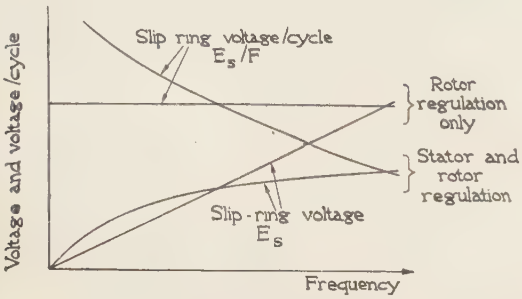
The fixed voltage E_A in Figs. 10(*b*) and 11(*b*) can also b produced by the secondary winding of a separate transforme the primary winding of which is connected to the supply. Suc an arrangement may, for instance, be required where an operatin condition is called for in which the stator winding of the frequenc convertor is disconnected from the supply (see Section 11.1).

(8.2) Combined Rotor- and Stator-Voltage Regulation

As with any commutator machine, speed variation can b obtained by rotor (armature) voltage regulation or by stato (field) voltage regulation or by a combination of both. Generall speaking, with a shunt commutator machine the speed adjust ment, and in the particular case of the frequency convertor unde

view, the slip-ring frequency adjustment, can be obtained by anging the ratio between the voltage applied to the stator and tor windings respectively. The results obtained by such mbined stator and rotor regulation are that the relationship tween the voltage and frequency at the slip rings of the conrtor can be modified in accordance with the requirements of fferent applications of the system.

Fig. 12 shows the voltage E_s at the slip rings of the convertor a function of the slip-ring frequency F, which is proportional the slip s.



g. 12.—Relation between frequency, slip-ring voltage and voltage per cycle with rotor-voltage regulation, and with an example of combined stator- and rotor-voltage regulation.

With rotor-voltage regulation the slip-ring voltage E_s is repreınted by a straight line [see also Fig. 2 and eqns. (1) and (2)], ıd the ratio between the slip-ring voltage and frequency, E_s/F, is nstant over the range.

By contrast with combined stator- and rotor-voltage regulation xecuted, for instance, with a booster transformer between the tor and stator circuit in accordance with Fig. 19—see Fig. 12 ıd also Fig. 12 of the author's earlier paper[2]) it is possible to btain, for instance, a function as represented by the curve shown Fig. 12, resulting in the ratio E_s/F increasing with lower freıencies. One of the main purposes for which such a system can e employed is to counteract the influence of the resistance in e variable-frequency circuit, the effect of which increases with ecreasing frequency (see Section 7). It is essentially the a.c. ator resistance, which, though small in itself and therefore ıving no material influence on the behaviour of the motor when perating with normal frequencies and voltages, creates a voltage op of considerable magnitude when compared with the voltages sociated with low frequencies.

The effect of increasing the ratio E_s/F, as in Fig. 12, is cumutive, since not only the voltage applied to the a.c. motor is latively increased at lower frequencies, thereby reducing the tio between active-voltage drop and applied voltage, but also increasing the magnetic flux of the a.c. motor a reduction of e current required for a given torque is obtained.

There are, moreover, other incentives for combined stator d rotor regulation for the frequency-convertor arrangement, ming at influencing the performance and characteristics of the c. motors supplied with variable frequency. Where the torque quired from these a.c. motors is not constant over their speed nge, the combined stator- and rotor-voltage regulation makes possible to adjust the flux of the a.c. motors, as represented oadly by the ratio E_s/F, so as to obtain optimum results with gard to losses, heating, efficiency and power factor, in accornce with the torque required at different speeds, exemplified fan and pump drives (falling torques) on the one hand and achine tools (constant outputs) on the other.

(8.3) Other Regulating Systems

Several regulating systems are available which use induction gulators and other variable-voltage transformers (e.g. see Section 9.2.4), the description of which is outside the scope of the paper, both for rotor-voltage regulation and for combined rotor- and stator-voltage regulation, including such systems where the rotor and stator circuits are connected in auto-transformer connection, using the same regulator for both purposes.

(9) VARIOUS OPERATIONAL CONDITIONS

(9.1) Starting and Reversing

(9.1.1) Starting the Convertor.

The convertor is started as a light-running shunt commutator motor, and this is done most economically by energizing the set with the induction regulator in the bottom-speed position referred to the convertor, so as to obtain the minimum starting current in the commutator circuit and the supply. Where combined stator- and rotor-voltage regulation is used, the starting operation of the convertor can be improved with regard to the voltage between commutator bars at standstill and low speeds (see Fig. 12).

(9.1.2) Starting the Variable-Frequency Motors.

The a.c. motors are connected to the slip rings at or near synchronous speed of the convertor, where there is little or no voltage and consequently current, so that the a.c. motors will remain at standstill. By adjustment of the induction regulator, the frequency and voltage at the slip rings is increased and the motors will develop a gradually increasing starting torque which is essentially determined by the resistances in the circuit, the reactances on the low-frequency side of the system being comparatively low, whereas the lagging currents taken by the induction motors are reflected as leading currents on the supply-frequency side and tend in combination with the reactances in that circuit to increase the commutator and slip-ring voltages.

Hence very high starting torques can be developed with minimum current which, moreover, through the action of the induction regulator, is reflected only to the extent of the effective transformation ratio to the line circuit (see Section 7). The start can, moreover, be made as smooth as desired, since the excess of motor torque over load torque is controllable by stepless adjustment.

So far as induction motors are concerned there is generally no necessity for using anything except squirrel-cage rotors (see Section 7). A further important result is that such squirrel-cage motors, whilst developing substantial torques, can be stalled for considerable periods without overheating. The rotor losses at low frequency are only of the order of the slip losses for the same torque at full speed, and not, as with motors supplied from a normal-frequency system, of the order of the synchronous output.

(9.1.3) Reversing the Variable-Frequency Motors.

The consideration of losses assumes an even greater importance for reversing, which is therefore preferably carried out at low frequencies in order to minimize heating. Reversing can, however, in principle also be obtained without any switching operation by an adjustment of the frequency-convertor speed through synchronism. As explained in Section 3.3, the change of the convertor speed from sub-synchronous to super-synchronous, or vice versa, results in a change of direction of rotation of the voltage vectors at the slip rings of the convertor, as represented by the straight-line frequency characteristic in Fig. 3, crossing the axis at synchronous speed. In this way a closed-loop circuit is obtained in the same way as through field reversal with Ward Leonard control. It is then only necessary to interrupt the slip-ring circuit for the purpose of starting the convertor. The

switch employed for the slip-ring circuit can then be operated virtually without current (see Section 9.1.2).

(9.2) Acceleration and Deceleration

The transient behaviour of the set during acceleration and deceleration of the variable-frequency a.c. motors is of considerable interest. It is not proposed to consider the mathematical treatment of this problem, but only to make a brief general statement regarding the interaction between the different elements of the set.

(9.2.1) Motor-Speed Changes.

The rate of acceleration or deceleration will in the first instance be determined by the rate of change of frequency, but the characteristics of the a.c. motor, the inertia of its rotor and the inertia of the driven machine naturally have an important influence. The excess of instantaneous motor torque over the steady load torque finally determines the acceleration or deceleration obtained under any transient condition. With quick decelerations and/or heavy inertia loads, the a.c. motor can become a generator, returning power to the line through the frequency convertor.

(9.2.2) Convertor Speed Changes.

The motoring or generating currents in the variable-frequency supply influence the behaviour of the frequency convertor. Superimposed on these currents are those required to accelerate or decelerate the rotor of the frequency convertor itself, which for the purpose of such speed changes acts as a commutator motor or generator, and during the transient period power is transferred across the air-gap.

The rate of acceleration or deceleration of the frequency-convertor rotor is controlled in the first place by the rate of change of the applied commutator voltage, which in its turn is a function of the rate of adjustment of the induction regulator.

The voltage drops caused by the acceleration and deceleration currents have to be considered, and at their face value such voltage drops will decrease the rate of speed change, as is normal with any control system based on rotor-voltage control. However, this does not represent the full picture, since in the same circuit the current producing the change of speed of the variable-frequency a.c. motor also flows.

(9.2.3) Speed Changes of Complete Set.

Obviously, the resultant voltage drop in the induction regulator is a function of the vectorial sum of the currents needed for the speed change of the a.c. motor and the convertor. With the frequency convertor operating in its sub-synchronous range, the amount of power and current taken from or returned to the supply through the induction regulator for any speed adjustment is only the difference between the power and currents required for the opposing speed changes of the two individual machines. In the ideal case, where the effective inertias of the frequency convertor and the motor with its load are equal, the system is completely balanced. The result of such balance is that the influence of the transient active accelerating or decelerating currents is eliminated both with regard to the voltage drop in the induction regulator as well as with regard to the supply.

The inertia of an induction motor is naturally low in comparison with that of an a.c. or d.c. commutator machine of the same output and speed. The frequency-convertor inertia is also lower than that of an equivalent commutator machine, since its rotor is small in view of the loss considerations (see Section 4.3).

There are no electromagnetic time lags comparable with those of a d.c. field system, although there is a short mechanical time delay connected with the adjustment of the induction regulator. This, in combination with the relatively low electro-mechanic time-constants of the system, results in an inherently qui transient response.

(9.2.4) Stepped Speed Changes.

Brief mention must be made of the possibility of sudd changes of the applied rotor voltage, i.e. the substitution of tap-changing transformer for the induction regulator as t source of adjustable voltage. This arrangement represents t fastest possible voltage adjustment, and it is interesting, therefor to examine the effect so obtained. Such a system is show diagrammatically in Fig. 13. A sudden change of applie

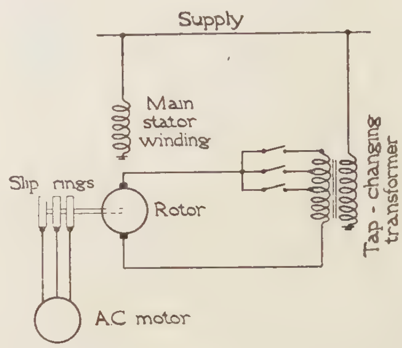


Fig. 13.—Rotor-voltage regulation by tap-changing.

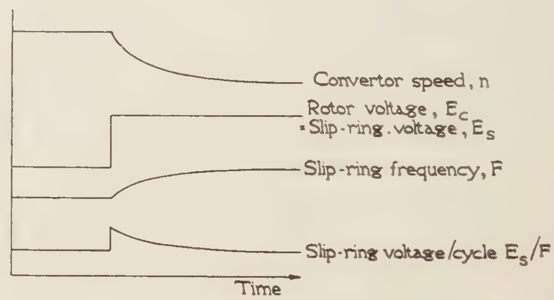


Fig. 14.—Transient conditions for sudden change of applied rotor voltage of the frequency convertor.

rotor voltage will produce a simultaneous change of th slip-ring voltage E_s (see Fig. 14) which is fed into the a. motor. However, it will not produce a sudden change of fr quency F, since the latter depends on the speed n of the co vertor, the change of which is determined by the electro-mech anical time-constants of the system (see Section 9.2.3). Co sequently the ratio of slip-ring voltage to slip-ring frequen E_s/F changes as shown in Fig. 14. As this ratio determines th flux of the induction motor, the torque developed by this machi is increased considerably, and with it the rate of change induction-motor speed. After the steady-state condition h been re-established, the ratio between slip-ring voltage and fr quency returns to its original value.

Similarly, a sudden reduction of voltage will produce a transie reduction of the voltage/frequency ratio at the slip rings, resulti in a negative torque producing regenerative action of the indu tion motor. The main effect is therefore a very quick respon to the change of frequency imposed on the motor.

Sudden changes of the voltage applied to the commutator any commutator machine, whether d.c. or a.c., are dangerou as is well known, and may lead to bad sparking and even flas over on the commutator. However, this danger is considerab

educed and, in practice, eliminated for quite considerable voltage changes with the described arrangement, since the closed slip-ring ircuit acts as a damping circuit for the transient changes of flux n the convertor.

(10) MULTI-MOTOR DRIVES

(10.1) General

This Section is largely concerned with practical applications of multi-motor drives. Naturally the multi-motor drive is articularly attractive, but it must be emphasized that there are nany examples of single-motor drives, e.g. flameproof motor or printing machine drive (see also SM4 of Fig. 16).

As has already been mentioned, any number of a.c. motors an be fed simultaneously from the slip rings of the convertor. This opens up the possibility of the simultaneous speed adjustment of a number of machines, and this has been utilized xtensively for the drive of individual roller table motors, coneyors and processing lines of various kinds, ranging over such liverse products as steel strip, pottery and Swiss rolls.

In order to visualize the behaviour of a group of such motors, clear distinction must be drawn between the behaviour of the vhole group and the behaviour of the individual motors with eference to one another.

For instance, if 100 independent induction motors are fed rom one frequency convertor and one of these motors were uddenly overloaded by 100%, the speed of the frequency conertor and the resultant frequency at the slip rings would be ffected only as if a change of load of 1% had occurred, i.e. uch a change would not be noticeable. The overloaded inducion motor would then reduce its speed compared with that of he group according to its own characteristic, which means that t would tend to slow down relative to the other motors of the roup.

It is conceivable, on the one hand, to give the whole group of notors any speed characteristic between those of the ideal shunt nd ideal series characteristics, whereas on the other hand the ndividual motors may be capable of assuming different speeds vith reference to one another, or be tied together with regard to heir individual speeds. The two extremes of the arrangements nay be represented by the two following combinations:

(*a*) An ideal shunt characteristic for the frequency convertor, i.e. load-independent speed and frequency combined with high-slip induction motors or series commutator motors, which can adjust their individual speeds in accordance with their load, or produce load sharing as the case may be.

(*b*) An arrangement whereby the speed and frequency of the frequency convertor is made load dependent, so that any load change of the group of motors will cause a large change of speed of the frequency convertor, and therefore of the frequency at the slip rings; whilst the a.c. motors are synchronous machines, or induction motors with little slip, so that their relative speeds are maintained whilst the speed of the group is load dependent.

Naturally there is room for many combinations of characeristics of motors and convertors between these limits in accorance with the requirements of individual drives. Some of the orque/speed characteristics required for the solution of all the roblems posed by practical applications can be obtained by the herent characteristics of the types and designs of machine sed, and others are obtainable by automatic control systems to uit the particular process.

(10.2) Synchronous Motors

If synchronous motors are used they will remain synchronized ith one another irrespective of the behaviour of the whole group, e. whatever the speed adjustment determined by the injected ommutator voltage of the convertor on the one hand and the peed/load characteristic of the whole set on the other.

The significance of this is that any load/speed characteristic of the whole group can be obtained either by the inherent characteristic of the design as set out in Section 6.5 or by automatic control of the injected commutator voltage, without disturbing the synchronization of the fed a.c. motors. It is therefore possible to obtain any desired behaviour of the whole group, including, for instance, complete load independence of the speed, or compound or series characteristic of the group, and still maintain absolute synchronization by the use of synchronous a.c. motors, as required for some process lines or sections thereof; e.g. a sectionalized plaster-board machine.

(10.3) Induction Motors

For the application of the system to a number of induction motors, the same principle applies, with the only difference that the individual induction motors may change their speed slightly owing to variations of slip. Any individual motor will therefore tend to slow down if a relatively heavier load is applied to it which is conducive to correct load sharing. The use of induction motors for group drives is therefore indicated where there is a mechanical connection between the individual drives, as for instance with conveyors, where the conveyor belt or chain represents such mechanical link. The same is true for roller tables, where the conveyed material requires such load-sharing behaviour of individual motors.

If small deviations from the average group speed have to be obtained, induction motors with rotor, or for small machines, stator resistance or line-voltage adjustment, can be employed for the purpose. The steel-strip descaling line shown diagrammatically in Fig. 15 employs small induction regulators to obtain

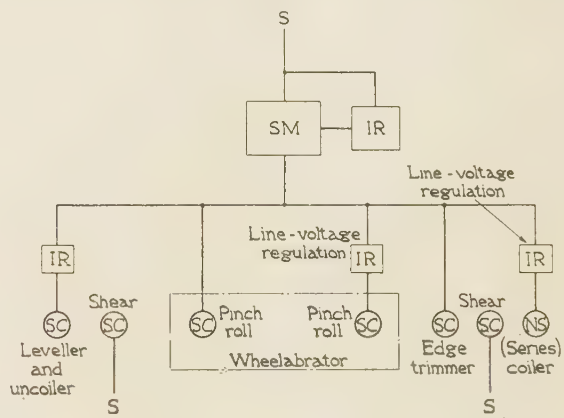


Fig. 15.—Block schematic of a steel-strip descaling line—Speedmaster-controlled multi-motor drive.

S: 3-phase supply.
SM: Speedmaster.
SC: Squirrel-cage motor.
NS: A.C. commutator motor.
IR: Induction regulator.

adjustable tension at the uncoiler and at the exit of the Wheelabrator in conjunction with variable-frequency squirrel-cage motors. It will be noted that in this diagram and also Fig. 16 (see Section 10.5) constant-speed (supply-line fed) induction motors are also utilized.

(10.4) Commutator Motors

For wider relative speed adjustments commutator motors are used. Assuming that one or more of the motors of the group controlled simultaneously are shunt commutator motors with induction regulator control, as in the arrangement shown in

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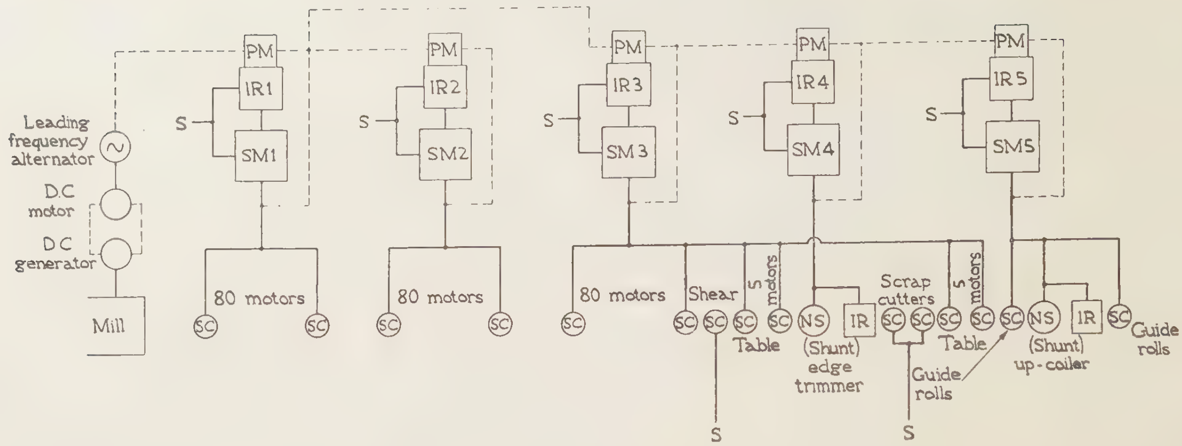

Fig. 16.—Block schematic of an aluminium-strip hot-run-out table—sectionalized Speedmaster-controlled multi-motor drives with automatic synchronization.

S: 3-phase supply.
SM: Speedmaster.
SC: Squirrel-cage motor.
NS: A.C. commutator motor.
IR : Induction regulator.
PM: Doubly fed slip-ring induction-type pilot motor.
——— Power connections.
- - - - Synchronizing control connections.

The three sections SM1–3, each comprising 80 individual roller table motors, can be operated in synchronism with each other and the mill or in synchronism with the edge trimmer and upcoiler SM4–5 as required by the progress of the strip.

Fig. 16 (SM4–SM5), the commutator motor in question can be considered as an induction motor for any fixed adjustment of its induction regulator. If that induction regulator is adjusted to zero voltage the commutator machine will run at the same speed as the induction motors of the group, since its slip is virtually the same for the nominal load. For any other voltage adjustment of the induction regulator, the basic speed of the commutator motor, as compared with that of the induction motors, is reduced or increased by a fixed amount referred to a given frequency. This amount changes, however, in proportion to the frequency applied to the whole group, so that the commutator motor speed will retain the same level relative to that of the group irrespective of the adjusted frequency. In other words "relative synchronization" is achieved.

The use of a series commutator motor is shown *inter alia* in Fig. 15, which makes it possible to utilize the inherent series characteristic of such a motor at all group speeds for the drive of the coiler, this arrangement being typical of continuous-process lines, where, apart from the reeler, the other driving motors are either induction motors or shunt commutator motors. The result of this combination is that constant tension in the reeled material can be maintained, irrespective of the adjusted group speed, which determines the linear speed of the processed material. The tension as such is adjusted by the induction regulator (see Fig. 15) giving line-voltage control. The alternative arrangement for phase-shift control between the stator and rotor circuit of the series commutator motor[2] can also be used.

(10.5) Synchronization of Convertor Groups

Reference should be made to the synchronization between a number of frequency convertors, i.e. group drives supplied for convenience of operation by two or more frequency convertors. For the purpose, any known system of synchronization can, of course, be used, but the fact that the frequency convertor produces a variable-frequency output opens up possibilities of exact synchronization by simple means. It may be necessary, moreover, to synchronize Speedmaster sets with other machines.

Fig. 16, showing diagrammatically the hot-run-out table of an aluminium strip mill,[6,7] illustrates examples of both synchronization requirements. The five frequency convertors SM1–5 are between themselves absolutely synchronized by utilizing double-wound induction-type pilot motors PM for the induction regulators IR1–5. Each pilot motor is connected with its stator winding to the output frequency supply of the preceding or "leading" Speedmaster, and with its rotor winding to the output frequency supply of the Speedmaster controlled by the induction regulator it serves. So long as there is any difference of frequency between its stator and rotor circuit, the pilot motor rotates as a doubly-fed synchronous machine until the frequencies are exactly equal, i.e. until absolute synchronization of the two supplies is obtained.

The pilot motor PM of the first Speedmaster SM1 ensures synchronization between the output frequency of that convertor and the frequency of an alternator which is driven by a small d.c. motor, whose speed is controlled by a Ward Leonard generator driven from a shaft of the last rolling-mill stand with which the a.c. roller-table motors supplied from the frequency convertors SM1–3 have to be synchronized. The d.c. generator produces a voltage proportional to the speed of that mill, and the d.c. motor will therefore run at a speed imparting to the leading frequency alternator a proportional frequency. An adjustment of the relative synchronization can be obtained by field regulation of either the generator or the motor.

The subdivision of the variable-frequency supply is necessary because the individual roller tables are alternatively automatically controlled from the speed of the rolling mill and by the operator of the trimmer and coiler drives (Speedmasters SM4–5).

(11) FREQUENCY CONVERTOR WITH SEPARATE DRIVING MOTOR

The arrangements so far treated utilize the self-propelling property of the described frequency convertor. However, it is possible to drive the frequency convertor from an auxiliary motor,[8] either for one or two singular speeds, or over the whole

peed and frequency range. The effect of such an arrangement s worth consideration in comparison with the well-known lip-ring-fed commutator frequency convertor, which has been used mainly with an auxiliary driving motor, although self-propelling arrangements of the latter type of frequency convertor nave been employed. This arrangement is the basis of the Schrage machine.[4]

(11.1) Drive by Single-Speed Motor

The drive of the frequency convertor by an independent uxiliary constant-speed motor is shown in Fig. 17. Such an

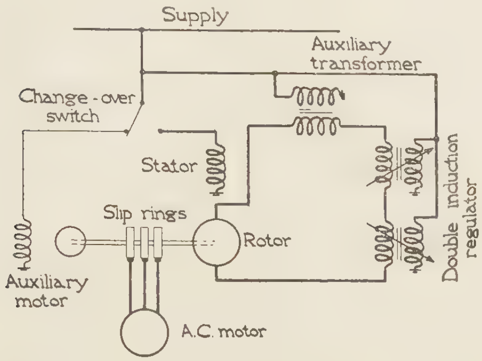

Fig. 17.—Separately-driven frequency convertor with single-speed motor drive.

uxiliary motor has to be designed only for the output required o overcome the friction and windage losses of the convertor, vith its stator winding disconnected from the supply. The load mposed on the auxiliary motor by the frequency convertor is hen clearly independent of the energy transfer from the com-nutator to the slip rings.

With the arrangement shown in Fig. 17, a load-independent requency is therefore obtained for one single speed determined y the speed of the auxiliary motor, and this can be used with dvantage to obtain a low load-independent frequency for the urpose of "crawling" of the fed a.c. motors, which is required, or instance, for the threading-in of materials in many processes n the textile, paper, printing, metal industries, etc. Equally, uitable low stable levelling speeds can be obtained for lifts and oists in this way.

The stator winding of the frequency convertor is brought into peration by the change-over switch, which at the same time isconnects the auxiliary motor, thus establishing the basic onnection discussed in previous Sections.

(11.2) Two-Speed and Adjustable-Speed Driving Motors

By the use of pole-change motors, two or more fixed speeds nd frequencies can be obtained. Adjustments of the "crawling" requency can be made by using a slip-ring auxiliary motor with otor-resistance regulation.

A variable-speed a.c. commutator motor enables the frequency o be varied over a wider range, the induction regulator for the onvertor being utilized simultaneously for the speed adjustment f the commutator motor and the voltage adjustment of the equency convertor (see Fig. 18).

(11.3) Comparison with Slip-Ring-Fed Convertor

The arrangement shown in Fig. 18 can also be applied to e conventional frequency convertor fed from the slip rings nd supplying low frequency at its commutator, which finds s application for low-frequency and narrow-frequency-range utputs.

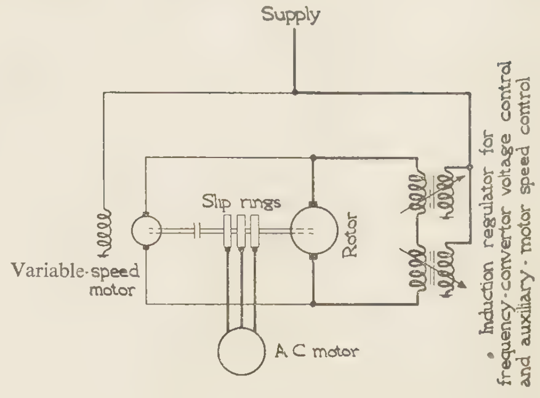

Fig. 18.—Separately-driven frequency convertor with variable-speed a.c. commutator motor drive.

(12) FREQUENCY CONVERTOR AS PHASE CONVERTOR

Reference has been made in Section 4 to the fact that the number of phases on the output side can generally be different from the number on the input side.

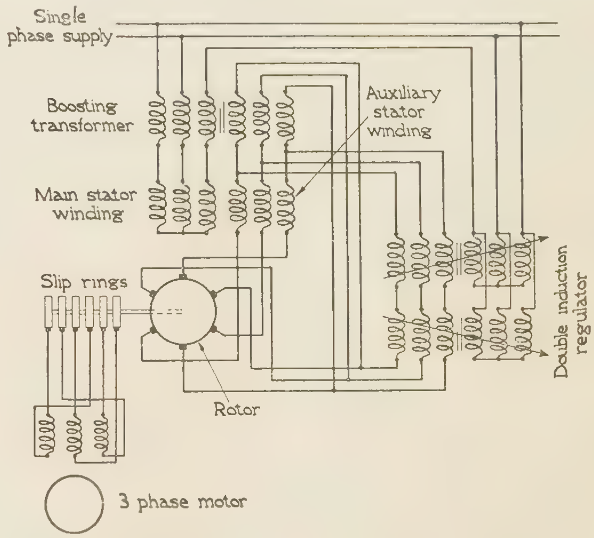

Fig. 19.—Main connection diagram of frequency/phase convertor.

Fig. 19 shows the broad principle of such an arrangement for converting a fixed-frequency single-phase supply into a variable-frequency 3-phase supply. The arrangement is on the lines of the basic arrangement of Fig. 10 used for a 3-phase supply, but with one supply phase omitted. The internal connections remain of a multi-phase nature, and a boosting transformer (see Section 8.2) is included. The frequency convertor, when rotating, is an efficient phase convertor, and practically balanced 3- or 6-phase voltages and currents are obtained under operating conditions of the set with the a.c. motors working as almost ideal multi-phase motors. The theory, design and application of this arrangement is envisaged as the subject of a future paper.

(13) ACKNOWLEDGMENTS

The author wishes to express his thanks to the directors of Laurence, Scott and Electromotors, Ltd., for permission to publish the paper, and to members of the technical staff for their valuable co-operation in developing the design and application of the machines described. Mr. K. K. Schwarz assisted in the preparation of the paper.

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(8) British Patent No. 588204.

(15) APPENDIX

(15.1) Calculation of Losses of m/m-Phase Rotor

Proceeding as illustrated for a 6/6-phase rotor in Section 4.2 and Fig. 4, for the general case of m commutator brushes and m slip-ring tappings, the resulting currents are found to be

$$I_\alpha = 2I_m \sin\frac{2\pi/m - \alpha}{2} \quad \text{and} \quad I'_\alpha = 2I_m \sin\frac{\alpha}{2}$$

where I_m is the internal current as a commutator machine, and α varies from 0 to $2\pi/m$.

Hence the loss W_α in m identical sections is

$$W_\alpha = \alpha\frac{R}{2\pi}\left(2I_m \sin\frac{2\pi/m - \alpha}{2}\right)^2 + (2\pi/m - \alpha)\frac{R}{2\pi}\left(2I_m \sin\frac{\alpha}{2}\right)^2$$

where R is the resistance of all rotor conductors in series. Th total mean loss is given by

$$W = \left(m\int_0^{2\pi/m} W_\alpha d\alpha\right)\Big/2\pi/m$$

$$= R\left(\frac{mI_m}{\pi}\right)^2\int_0^{2\pi/m}\left[\alpha\left(\sin\frac{2\pi/m - \alpha}{2}\right)^2 + (2\pi/m - \alpha)\left(\sin\frac{\alpha}{2}\right)^2\right]d$$

$$= 2R\left(\frac{mI_m}{\pi}\right)^2\left[\left(\frac{\pi}{m}\right)^2 - \left(\sin\frac{\pi}{m}\right)^2\right]$$

But $I_m = \dfrac{3I}{m \sin \pi/m}$, where I = internal (= external) curren for 6/6-phase rotor for a given kVA output.

Hence $$W = 1\cdot 83RI^2\left[\frac{(\pi/m)^2}{(\sin \pi/m)^2} - 1\right]$$

(15.2) Calculation of Losses of Rotor Generally

The loss for any other combination of ingoing and outgoin phases can be similarly derived. For the particular case of th $m/\frac{1}{2}m$-phase rotor windings of Table 1,

$$W = 1\cdot 83RI^2\left[\frac{1 + (\sec \pi/m)^2}{2(\sin \pi/m)^2}\left(\frac{\pi}{m}\right)^2 - 1\right]$$

DISCUSSION ON "THE DAMAGE TO LEAD-SHEATHED CABLES BY RODENTS AND INSECTS"*

Mr. M. P. Wax (*communicated*): Fig. A shows the part of a two-core p.v.c.-insulated cable which runs in a duct of 6in diameter and about 2ft length through the outside wall of a building on the top of an isolated hill in the Orkney Islands. The duct seems to be used as an entrance by rats. There are two armoured cables of about 2in diameter in the same duct, but these show no signs of damage.

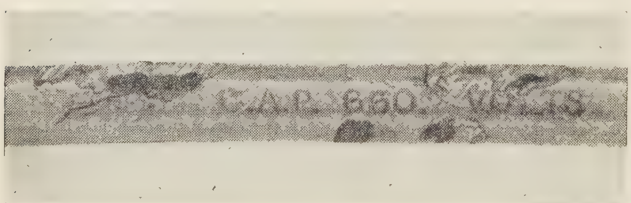

Fig. A.—Specimen of p.v.c.-insulated cable gnawn by rats.
Damage considerably worse than that depicted above has been known.

There is no possibility of these rats being conditioned to expect water, for there is no piped water supply within four miles, and the nearest building—a farm—is over a half-mile away. The need to gnaw is a more likely explanation, and the immunity of the armoured cables may be due to their larger diameter, makin gnawing more difficult.

Other p.v.c. cables have been gnawn, in some cases righ through; with the exception of one, near the outer end of th duct, they were lying on the bench in the building itself.

In all cases, much of the p.v.c. debris has been removed b the rats, perhaps for nest-making. I have frequently found wast matter removed, apparently for this purpose, and occasionall chewed-up paper from drawings which had been left lying abou

Mr. J. F. Giblin and **W. T. King** (*in reply*): We thank M Wax for bringing to our notice this most interesting sample o p.v.c.-insulated cable gnawn by rats. From the evidence o damage to lead-sheathed cables by rats we would expect to fin examples of damage to similar soft materials such as p.v. Fig. A shows this type of damage very clearly indeed, and w would agree that this example substantiates the view that suc damage is produced during the normal habit of maintaining th teeth in good condition.

Mr. Wax's information that armoured cables in the same duc as the damaged p.v.c. cable were undamaged is most interestin This is the first definite observation of its kind of which we ar aware. An alternative explanation to that of Mr. Wax migh be that the armour, since it probably consisted of a hard meta such as steel, did not show the effects of gnawing. If this wer the case, engineers may find it useful to consider armouring a an anti-rodent protection.

* GIBLIN, J. F., and KING, W. T.: Paper No. 1641 S, May, 1954 (see **101**, Part I, p. 123).

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Paper No. 1784 U
Feb. 1955

THE OPERATION OF THREE-PHASE INDUCTION MOTORS WITH UNSYMMETRICAL IMPEDANCE IN THE SECONDARY CIRCUIT

By T. H. BARTON, Ph.D., B.Eng., and B. C. DOXEY, B.Eng., Graduates.

(*The paper was first received* 28*th July, and in revised form* 22*nd October*, 1954.)

SUMMARY

The operation of an induction motor at one-half normal speed against appreciable load, by means of unbalanced impedance in the secondary circuit, is shown to be a practicable possibility with accurately predictable characteristics. Precautions must be taken to prevent saturation of the main magnetic circuit of the machine, and in some cases it may be essential to limit the injection of low-frequency currents into the supply system. Simple solutions to these problems are described, and it is concluded that the method has sufficient merits to justify its use in certain applications where a speed reduction to about one-half the normal value is required.

LIST OF SYMBOLS

The suffixes r, y and b represent the red, yellow and blue phases, respectively.

The suffixes a and c represent the primary and secondary of any phase of the machine, respectively.

The suffixes 0, 1 and 2 represent zero-, positive -and negative-sequence components, respectively.

The above suffixes may appear either singly or together in conjunction with:

V = Voltage.
I = Phase currents.
Z = Phase impedances.
R = Phase resistances.
X = Phase reactances.
$a = \varepsilon^{j120°}$.
f_0 = Supply frequency.
ω_0 = Supply angular frequency.
s = Fractional slip.
R_m = Magnetizing resistance.
X_m = Magnetizing reactance.

(1) INTRODUCTION

The phenomenon of stable half-speed operation of a polyphase induction motor with one secondary phase open-circuited was first noted by Görge[1] in 1896. It has been discussed a number of times since then, the latest contribution being by Garbarino and Gross,[2] who include a complete bibliography. However, although the possibility of reasonably efficient half-speed operation is attractive, the method is hardly ever used in practice. There are three reasons for this—the injection of low-frequency currents into the supply, mechanical vibration and magnetic saturation leading to excessive currents. The importance of these factors has not been realized by previous theoretical investigators, because effort has been directed to the prediction and verification of the complete torque/speed characteristic, the experimental work being necessarily performed at reduced voltage and thereby almost eliminating the above effects. Experience by the authors of operation at normal voltage in the half-speed region has led to the development of simple methods for reducing these effects to reasonable proportions.

(2) THEORY

(2.1) The Equivalent Circuit

The application of a positive-sequence voltage system of amplitude V_{a1} and frequency f_0 to the primary terminals of a symmetrical induction motor produces a distributed magnetic field in its air-gap which is essentially sinusoidal and rotates forwards relative to the primary circuit at synchronous speed ω_0. The field rotates forwards relative to the secondary circuit with a velocity $s\omega_0$ and induces in its windings a positive-sequence e.m.f. system of voltage sV_1 and frequency sf_0, which causes positive-sequence currents to flow in the secondary impedances. The primary and secondary positive-sequence currents satisfy the m.m.f. balance equation, so that the difference of their m.m.f.'s just produces the positive-sequence flux. The positive-sequence equivalent circuit of the machine, assuming a turns ratio of unity, is shown in Fig. 1. This differs from the

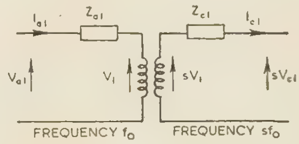

Fig. 1.—Positive-sequence equivalent circuit.

normal equivalent circuit in that the positive-sequence voltage, sV_{c1}, across the external secondary impedance is inserted instead of an impedance.

If the secondary external impedance is unsymmetrical, the flow of positive-sequence current through it generates negative-sequence voltages of the same frequency at its terminals. These are, of course, the secondary terminals of the machine, so that a negative-sequence magnetic field is also produced in the air-gap of the machine. This rotates backwards relative to the secondary circuit with a velocity $s\omega_0$ and backwards relative to the primary circuit with a velocity $(2s-1)\omega_0$. The negative-sequence voltages induced in the primary windings by this field have a frequency $(2s - 1)f_0$, and produce negative-sequence currents in the balanced primary impedance, since the supply short-circuits all frequencies other than f_0. Again, the difference of the secondary and primary negative-sequence m.m.f.'s must be just sufficient to produce the negative-sequence flux. The equivalent circuit of the negative-sequence system is shown in Fig. 2.

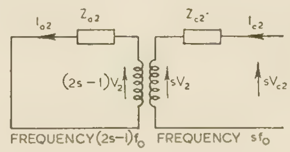

Fig. 2.—Negative-sequence equivalent circuit.

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.

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The equations of performance can be derived from the two equivalent circuits, provided that the relationship between the positive- and negative-sequence secondary terminal voltages, sV_{c1} and sV_{c2}, can be established. This is done in Section 9.1 by considering the symmetrical components of the external secondary impedance. Restricting consideration to machines with star-connected secondary circuits and isolated neutrals, so that no zero-sequence current can flow, the desired relationship is given by

$$sV_{c1} = I_{c1}Z_0 - I_{c2}Z_2$$

$$sV_{c2} = -I_{c1}Z_1 + I_{c2}Z_0$$

By analogy with the mutual-inductance equation

$$V_1 = I_1X_{11} - I_2X_{12}$$

$$V_2 = -I_1X_{12} + I_2X_{22}$$

the above equations represent an asymmetric mutual-impedance link between the positive- and negative-sequence networks which can therefore be combined into the one equivalent circuit of Fig. 3.

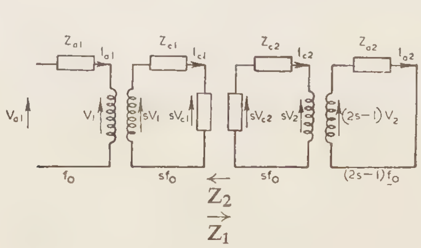

Fig. 3.—Combined equivalent circuit.

(2.2) The Torque

The output torque of the machine has two components—that produced by the positive-sequence system, and that produced by the negative-sequence system. Alternating torques are produced by interaction between the systems, and these produce mechanical vibration, although they contribute nothing to the output, having a mean value of zero. The positive-sequence torque is the mean power crossing the air-gap from primary to secondary circuit, i.e. it is V_1I_{c1} synchronous watts per phase. The direction of torque is such as to drive the secondary circuit forwards when positive and backwards when negative. The power crossing the air-gap from secondary to primary circuit, sV_2I_{a2} watts per phase, provides the negative-sequence torque. However, since this corresponds to a synchronous speed of $s\omega_0$, the torque at base synchronous speed, ω_0, is V_2I_{a2} synchronous watts. The direction of this torque is derived from the following considerations. The negative-sequence field originates in the secondary circuit of the machine and rotates backwards relative to it with a velocity $s\omega_0$. The velocity of the primary circuit relative to the secondary circuit is $(1 - s)\omega_0$ backwards, so that if $(1 - s)$ is greater than s, i.e. $s < \frac{1}{2}$, there is a forward torque on the primary circuit and a backward torque on the secondary circuit. Alternatively, if $s > \frac{1}{2}$ the negative-sequence torque on the secondary circuit acts in a forward direction. When $s = \frac{1}{2}$, the negative-sequence torque is zero. These results are summarized in Table 1.

(2.3) Computation, with Some Modifications to the Equivalent Circuit

Although the equivalent circuit of Fig. 3 is an extremely compact statement of the performance equations of the machine, its solution by ordinary means is an extremely laborious task. The computation can be by-passed by converting the circuit to

Table 1

Speed	Slip	Torque direction	
		Positive-sequence	Negative-sequence
$< \frac{1}{2}\omega_0$	$> \frac{1}{2}$	Forward	Forward
$\frac{1}{2}\omega_0$	$\frac{1}{2}$	Forward	Zero
$\frac{1}{2}\omega_0 < \omega < \omega_0$	$\frac{1}{2} > s > 0$	Forward	Backward
ω_0	0	Zero	Zero
$> \omega_0$	< 0	Backward	Backward

constant frequency in the usual way, and setting up the resultant circuit on an analyser of the Blackburn type, which is capable of simulating unsymmetrical mutual impedance. However, in the absence of such an aid, the authors have restricted their investigations to cases where the positive- and negative-sequence components of the external secondary impedance are equal. This makes the mutual impedance symmetrical and considerably reduces the labour of computation. This desirable condition is obtained if the external impedance is symmetrical about one phase, which is to be taken as the datum phase. Taking the red phase as the datum, $Z_y = Z_b \neq Z_r$, and as shown in Section 9

$$Z_0 = \tfrac{1}{3}(Z_r + 2Z_y)$$

$$Z_1 = Z_2 = \tfrac{1}{3}(Z_r - Z_y)$$

The resultant equivalent circuit converted to constant frequency f_0, and with the mutual impedance replaced by its equivalent T-network, is shown in Fig. 4.

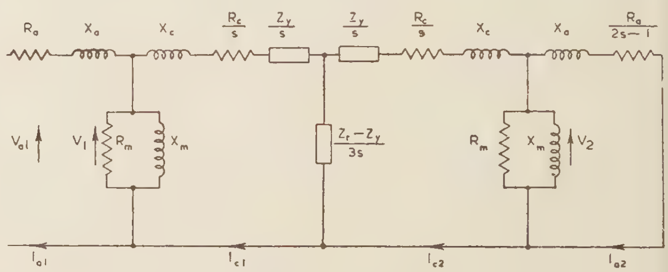

Fig. 4.—Simplified equivalent circuit.

The performance characteristics are determined by first deriving the input impedance of the equivalent circuit of Fig. 4, noting the impedance at each intermediate stage. Under unsaturated conditions the magnetizing impedances can be neglected.

The input current is then calculated, together with the intermediate currents and voltages I_{c1}, I_{a2}, V_1 and V_2. The output torque is the algebraic sum of the sequence torques, i.e. $V_1I_{c1} + V_2I_{a2}$ synchronous watts per phase. The primary phase current is $\sqrt{(I_{a1}^2 + I_{a2}^2)}$, since the two components are at different frequencies. The secondary phase currents are the vector sums

$$I_r = I_{c1} + I_{c2}$$

$$I_y = a^2I_{c1} + aI_{c2}$$

$$I_b = aI_{c1} + a^2I_{c2}$$

since the components are at the same frequency.

Algebraic solutions for these quantities in terms of circuit parameters are too complicated to be of much value in the analysis of performance. Numerical solutions for certain typical cases are more easily obtained, and when plotted as suitable graphs can give the desired information.

(3) THE OPERATING CHARACTERISTICS

To demonstrate the possibilities of this method of control, the torque/speed characteristics of Figs. 5 and 6 have been calculated for a 15h.p. induction motor, which was used for much of the experimental work. The details of the machine are as follows:

The stator carries a 3-phase primary winding having six poles and rated at 400 volts, 12amp per phase at 50c/s. The rotor carries a 3-phase secondary winding, star-connected to three slip rings and with isolated neutral. The positive-sequence parameters, referred to the primary winding, and at the normal operating temperature are

	ohms per phase
Primary resistance	1·33
Secondary resistance	2·78
Primary leakage reactance	3·85
Secondary leakage reactance	3·85
Magnetizing reactance	84·4

Torques and currents are expressed as percentages of the normal rated values, and to avoid optimistic misconceptions, they have been calculated assuming a phase voltage of only $1/\sqrt{3}$ times the rated value. The reason for this is that such a voltage is close to the maximum that can be applied to a machine with one secondary phase open-circuited if gross magnetic saturation is to be avoided. The point is discussed in detail in Section 5.6.

The characteristics of Fig. 5 were computed assuming the datum secondary phase to be open-circuited, i.e. Z_r of Fig. 4 infinite. The effect of varying the secondary resistance, whilst maintaining the primary resistance constant, is shown in Fig. 5A.

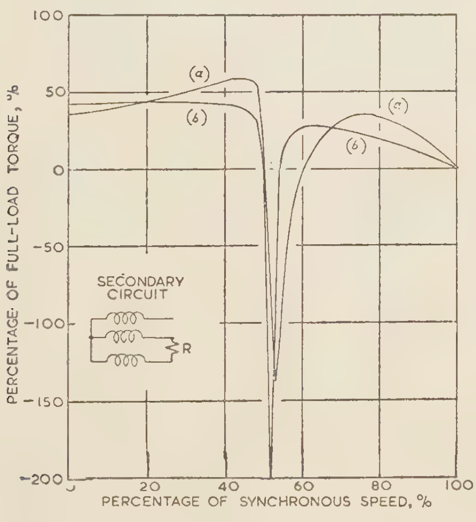

Fig. 5A.—Theoretical torque/speed characteristics when one phase is open-circuited, showing the effect of increasing the secondary resistance.

Phase voltage is $1/\sqrt{3}$ times the normal value.
(a) $R = 0$.
(b) $R = 9 \cdot 3$ ohms referred to the primary.

Fig. 5B shows the effect of varying the primary resistance, the secondary resistance being constant. The negative-torque region, extending from half synchronous speed some way towards synchronous speed, which permits stable half-speed operation, will be noted. The magnitude of the negative-torque peak is increased by an increase in either primary or secondary resistance, and the speed range over which negative torques are obtained is increased by an increase in primary resistance and decreased by an increase in secondary resistance. The slope of the characteristics at half speed is decreased by an increase in either

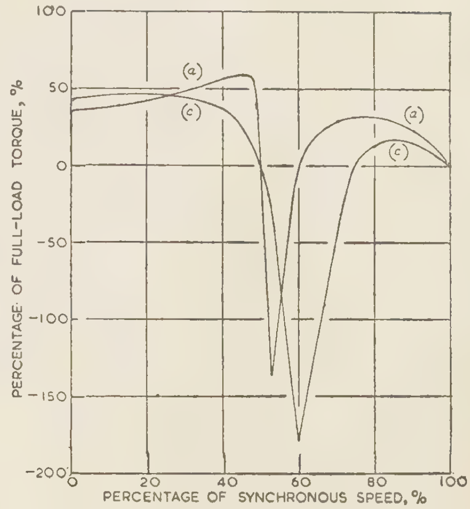

Fig. 5B.—Theoretical torque/speed characteristics when one secondary phase is open-circuited, showing the effect of increasing the primary resistance.

(a) No external impedance in primary circuit.
(c) External primary resistance of 4·96 ohms per phase.
Phase voltage is $1/\sqrt{3}$ times the normal value.

resistance. The peak motoring torque available below half speed is little affected by the secondary resistance, but is appreciably decreased as the primary resistance is increased.

The effect of decreasing Z_r from infinity to zero, whilst maintaining the primary and secondary resistances constant at their normal values, is shown in Fig. 6. The impedance is assumed

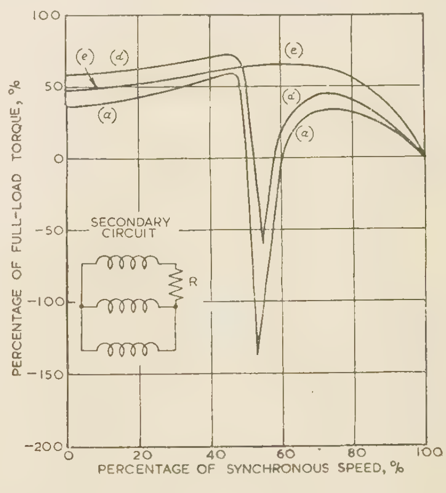

Fig. 6.—Theoretical torque/speed characteristics with resistance in series with one secondary phase.

Phase voltage is $1/\sqrt{3}$ times the normal value.

to be purely resistive, since additional reactance has a deleterious effect on performance similar to that obtained in normal symmetrical operation. As the resistance is decreased the connection approaches closer to symmetry, and consequently the negative-torque peak is decreased until, at some critical resistance, the half-speed dip fails to pass below the axis into the negative-torque region. This is the minimum resistance for stable half-speed operation at no load. However, stable half-speed operation against load can still be obtained at considerably lower resistances. Two points of special importance about these characteristics

are that their slopes at half speed are little affected by the change in resistance, and the speed at which zero torque occurs is increased slightly above one-half synchronous speed as the resistance is decreased. This is significant in that considerable torques can then be obtained at exactly one-half synchronous speed.

To reduce the labour of computation the magnetizing reactances have been neglected—a permissible approximation provided that the magnetic circuit remains unsaturated. The current drawn by the negative-sequence magnetizing reactance of Fig. 4 passes twice through the secondary resistance, and therefore increases the positive-sequence torque. This causes the zero-torque point to be moved to a speed higher than that shown on the graphs. However, the shift is too small to be experimentally detected. The effect on the electrical characteristics is to increase the power factor at all speeds.

(4) EXPERIMENTAL VERIFICATION OF THE THEORY

The performance of the machine described in the preceding Section has been predicted and measured for numerous conditions of unbalance in its secondary circuit. Some of the results of these tests are shown in Figs. 7, 8 and 9. The curves are

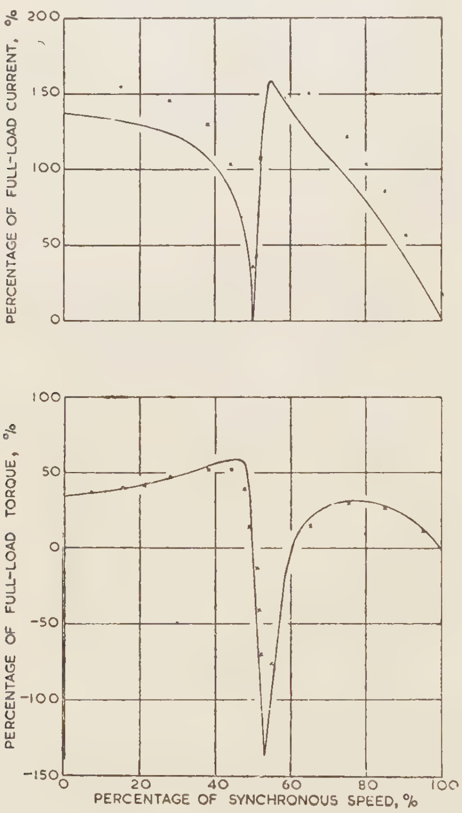

Fig. 7.—Current/speed and torque/speed characteristics when one secondary phase is open-circuited.

Phase voltage is $1/\sqrt{3}$ times the normal value.
——— Predicted.
× × × Experimental.

predicted using the equivalent circuit of Fig. 4, but neglecting the magnetizing impedances, whilst the points are obtained experimentally. It will be seen that agreement between predicted and experimental data is everywhere reasonably close, any discrepancies being such as would be expected from the above simplification of the equivalent circuit and the effects of stray load loss.

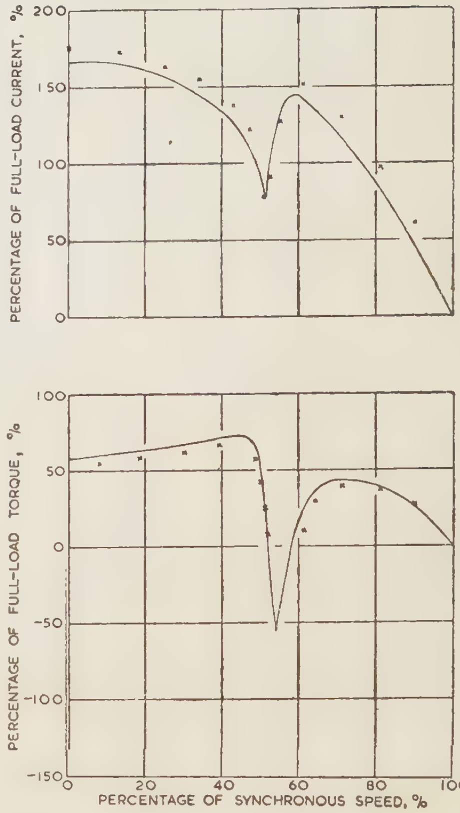

Fig. 8.—Current/speed and torque/speed characteristics with a resistance of 20·2 ohms in series with one secondary phase.

Phase voltage is $1/\sqrt{3}$ times the normal value.
——— Predicted.
× × × Experimental.

Thus all predicted currents are somewhat lower and predicted power factors somewhat higher than the measured values because of the neglected magnetizing currents, and all predicted torques are a little too high because of the retardation produced by the stray load loss.

(5) PRACTICAL APPLICATIONS

The foregoing characteristics show that, by the use of unsymmetrical resistance in its secondary circuit, it is technically possible to operate an induction motor stably at one-half its normal speed against appreciable loads. Also they demonstrate that control of speed between one-half and the normal value cannot be effected by this means. The practical utility of the method depends upon additional factors not yet discussed, namely

(*a*) Starting procedure or, more generally, the means by which half speed is attained.
(*b*) The magnitude of loads which can be driven at one-half normal speed.
(*c*) The efficiency of operation.
(*d*) The energy dissipated inside the machine.
(*e*) The injection of negative-sequence currents into the supply system.
(*f*) The effect of saturation in the main magnetic circuit of the machine.
(*g*) The possibility of electro-mechanical vibrations in the unsymmetrically loaded machine.

(5.1) Starting Procedure

The characteristics of Figs. 7, 8 and 9 show that starting torques of the same order of magnitude as the half-speed

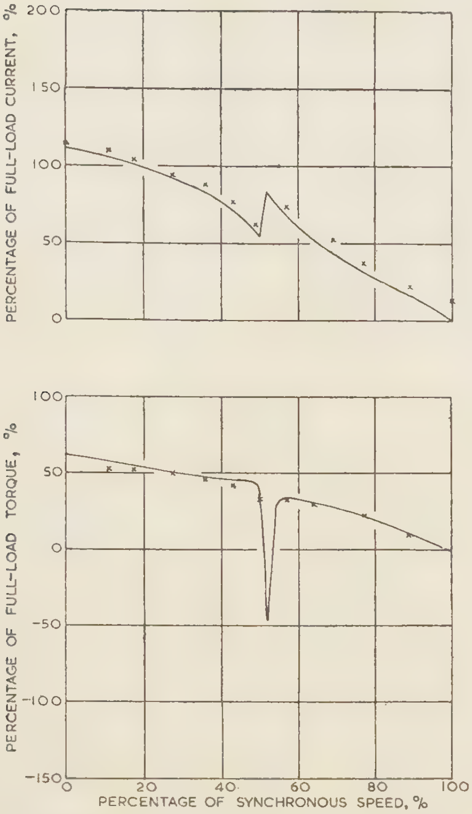

Fig. 9.—Current/speed and torque/speed characteristics with resistances of 20·2 ohms in series with two secondary phases.

Phase voltage is $1/\sqrt{3}$ times the normal value.
——— Predicted.
× × Experimental.

unning torque are obtained and that the starting currents are no more severe than those normally obtained. During the unning-up period the frequency of the negative-sequence currents injected into the supply system will change from supply requency at standstill to a low value at speeds close to one-half ynchronous speed. These currents decrease as the machine uns up because of the behaviour of the term $R_a/(2s - 1)$ in he negative-sequence circuit. Hence, provided that the negative-equence current can be accepted by the supply system, there hould be no difficulty in starting the machine.

The opposite procedure, that of running down from full speed o half speed, presents more difficulty because of the positive-orque region just below synchronous speed. It is possible to educe the speed down to one-half the normal value only if the oad torque exceeds the maximum torque in this region. The atter torque is reduced to a minimum by having the maximum symmetry in the secondary circuit and the highest possible atio of primary to referred secondary resistance per phase. However, too great an increase in this ratio results in a reduction n the half-speed motoring torque, and no overall gain is obtained.

(5.2) Magnitude of Half-Speed Load

Saturation of the main magnetic circuit of the machine, liscussed in Section 5.6, limits the applied phase voltage at educed speed to about $1/\sqrt{3}$ times the normal value. At this oltage the maximum half-speed torque is between 50 and 80% f the normal rated torque. The available torque is increased rom the lower value to the higher as the asymmetry in the econdary circuit is reduced. However, as indicated in Section 5.6, comparatively small increase in the dimensions of the machine enables the voltage to be maintained at the normal value when operating at reduced speed. The maximum torque is then raised to 90–140% of the rated value. The r.m.s. primary current required to give the torques mentioned above will in either case be between 90 and 110% of the normal rated value.

In special cases where the load torque at half speed is always considerable, it is possible to use resistance in series with two secondary phases instead of one. This lessens the asymmetry in the secondary circuit and enables higher voltages and load torques to be applied to the machine, at the expense of a reduction in efficiency.

(5.3) The Efficiency of Half-Speed Operation

The efficiency of a normal induction motor is always less than $(1 - s)$, i.e. at one-half the normal speed it is less than 50%. In a machine with unsymmetrical resistance in its secondary circuit the efficiency can exceed $(1 - s)$ because some of the apparent positive-sequence power loss in the secondary circuit is actually used to generate the negative-sequence system and thus contributes again to the power output. Where a resistance R (referred to the primary circuit) is connected in series with one secondary phase, the efficiency, η, neglecting the magnetizing impedances, may be expressed as

$$\eta = (1 - s)\left[1 + \frac{\left|\dfrac{Z_y}{Z_x + Z_y}\right|^2 \dfrac{R_a}{2s - 1} - R_a}{R_a + \dfrac{R_c}{s} + \left|\dfrac{Z_y}{Z_x + Z_y}\right|^2 \left(\dfrac{R_c}{s} + \dfrac{R_a}{2s - 1}\right) + \left|\dfrac{Z_x}{Z_x + Z_y}\right|^2 \dfrac{R}{3s}}\right]$$

where $Z_x = \dfrac{R_c}{s} + \dfrac{R_a}{2s - 1} + j(X_a + X_c)$

and $Z_y = \dfrac{R}{3s}$

Putting $R = \infty$

$$\eta = (1 - s)\left(\frac{\dfrac{2R_a}{2s - 1} + \dfrac{2R_c}{s}}{R_a + \dfrac{2R_c}{s} + \dfrac{R_a}{2s - 1}}\right)$$

when one secondary phase is open-circuited. In practice the efficiency is somewhat less than these equations indicate owing to the losses associated with the magnetizing currents. The calculated efficiencies of the experimental machine for $R = \infty$, $60\,R_c$ and $30R_c$ are plotted as functions of speed in Fig. 10. Experimentally determined values confirm these calculations. It will be noted that, at the operating speed, the efficiency of the machine with one secondary phase open-circuited is high—of the order of 80%—and that it is reduced as R is decreased. This is to be expected since the external secondary resistance tends towards a symmetrical arrangement with reduction in R. Hence, in order to obtain maximum efficiency, R should have the maximum possible value consistent with other requirements.

(5.4) Internal Energy Loss

The temperature rise, and hence the output of the machine, depends upon the rate at which energy is dissipated inside it. Hence, for a machine operating at one particular speed, the output torque per unit of internal loss is a figure of merit hardly less important than the efficiency. With the connections under discussion the internal losses are

Primary loss $= R_a(I_{a1}^2 + I_{a2}^2)$ watts per phase.

Secondary loss $= R_c(I_{c1}^2 + I_{c2}^2)$ watts per phase.

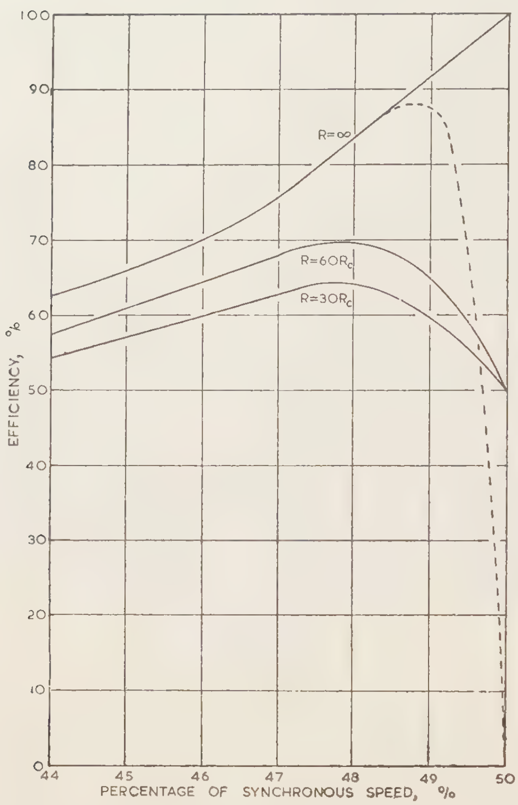

Fig. 10.—Efficiency/speed characteristics for various resistances in series with one secondary phase.

- - - - - Effect of magnetizing impedance.

The torque output per unit of internal loss depends greatly upon the precise speed and the form of the external secondary impedance. Since these factors are fixed more by considerations external to the machine than by the machine itself, it is profitless to discuss the exact value of the above quantity. However, a general view shows that, since in the working region both the positive- and negative-sequence systems contribute to the output torque, the figure of merit need not be greatly inferior to that of a machine with symmetrical secondary impedance.

The maximum torque deduced from a consideration of the mean loss per phase in the machine will be somewhat higher than would be continuously available in practice, since the loss in the secondary circuit is not distributed uniformly between the phases; e.g. if one secondary phase is open-circuited the whole secondary loss, $3R_c(I_{1c}^2 + I_{2c}^2)$, occurs in the two others. The exact amount by which the machine must be derated depends upon the degree of temperature equalization between the unequally heated phases.

(5.5) Negative-Sequence Supply Currents

The negative-sequence current injected into the supply, I_{a2} of Fig. 4, has a frequency $(2s - 1)f_0$. This is a small fraction of the supply frequency when the speed is close to one-half synchronous speed. With the normal Görge connection of one secondary phase open-circuited, the positive- and negative-sequence currents in the supply are nearly equal, since Z_r of Fig. 4 is infinite. Thus, when the machine is loaded, the negative-sequence current becomes appreciable. The spread of this low-frequency current through the supply network will not be objectionable in many cases, but in situations where the power consumed by the reduced-speed machine is an appreciable component of the local power requirement, measures to reduce its effect are essential. The negative-sequence supply current can be completely eliminated by operating at exactly one-half synchronous speed, because the term $R_a/(2s - 1)$ is then infinite. This desirable condition can be obtained when on load by using a suitable resistance in series with the third phase. The specific value required at each load is readily predictable by the method of Section 9.2. This requirement of varying resistance with load may be considered too complex when compared with, for example, a change-pole motor for the same duty. However, in applications where the load at reduced speed does not vary greatly, one value of secondary resistance can suffice to keep the negative-sequence current low at all times.

(5.6) Magnetic Saturation

The positive- and negative-sequence magnetic fields, which are proportional to the voltages V_1 and V_2, co-exist in the machine. They rotate at different speeds so that sometimes they aid and sometimes they oppose. At the former instants, even though the peak flux densities of the individual fields are reasonable, their combination results in gross saturation. The usual undesirable consequences follow—there is a considerable increase in the magnetizing currents and a deterioration in their waveform. It is to be expected that saturation will begin to be apparent when the sum of the peak flux densities of the two component fields exceeds the normal peak flux density in the machine. Neglecting second-order effects, this will be when the sum of the voltages V_1 and V_2 exceeds the normal phase voltage. This is confirmed by Fig. 11, which shows open-circuit characteristics for the symmetrical machine and for the machine with one secondary phase open-circuited, taken at synchronous and one-half synchronous speed, respectively. The normal phase voltage is 400 volts, giving a magnetizing current of 4·6 amp. With the unsymmetrical secondary circuit, an equal magnetizing current is obtained at a phase voltage of 220 volts. Also, it is apparent that this machine could not be operated at full voltage with this particular type of secondary-circuit asymmetry, because the magnetizing current would then far exceed the normal full-load current of 12 amp.

The magnetic conditions have been alleviated by three methods —reduction in supply voltage, introduction of additional primary impedance, and the introduction of additional secondary impedance. A fourth method, available for use in a practical application, is an increase in the frame size of the motor above that necessary for normal operation. As Fig. 11 shows, a reduction in the supply voltage to about one-half the normal value gives approximately normal magnetic conditions. This reduction can be obtained by any suitable method, but probably the only one of practical value is the operation of a normally delta-connected machine in star. This gives a reduction to 58% of the normal phase voltage, and will give a magnetizing current of 4·9 amp, i.e. 107% of the normal value, with the characteristics of Figs. 5 and 6. The method is open to the objection that the maximum torque obtainable at half speed with full load current is about 60% of the normal full-load value.

The addition of impedance in series with the primary circuit results in a reduction of the voltages appearing across both magnetizing reactances. The torque/speed characteristics of Fig. 5 show that the resistive component of this impedance should be as small as possible if large speed regulation, with change in load, is to be avoided. The positive-sequence current drawn from the supply normally lags by about 50°, so that a large reduction in voltage, without a correspondingly large diminution in power factor, can be obtained by the use of series inductances. These can be made saturable if desired, in order to make use of the voltage drop in the primary resistance and leakage reactance

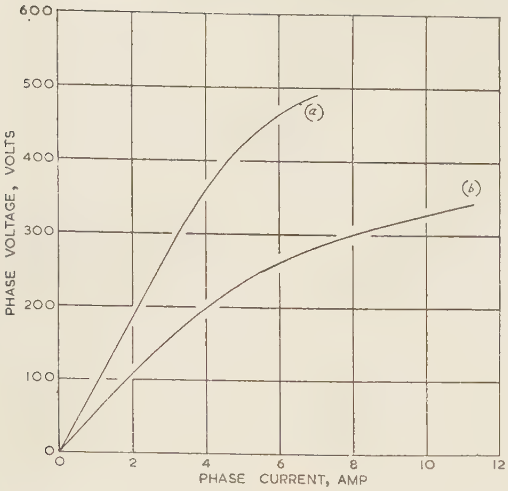

Fig. 11.—Open-circuit characteristic of normal machine [curve (*a*)] and machine with one secondary phase open-circuited at half synchronous speed [curve (*b*)].

at the higher currents. The method, although possibly more expensive than the previous one, has the advantage of not being restricted in voltage. The voltage appearing at the terminals can be adjusted to suit the magnetization characteristic, and somewhat higher torques can be obtained, say 80–100% of normal full-load torque.

Results obtained in practice with these methods are shown in Fig. 12. This shows torques and currents experimentally obtained at speeds close to half synchronous speeds. Curves (*a*) are for a reduction of phase voltage to $1/\sqrt{3}$ times the normal value. The torque available at half speed is 0·4 times the normal full-load torque for a current of 0·9 times the full-load current, with a pull-out torque of 0·7 times the full-load torque at a current of 1·25 times the full-load current. Curves (*b*) are at normal voltage but with 6 ohms per phase of added primary reactance. The torques available at half speed and pull-out are increased to 0·6 and 0·9 times the full-load value, the corresponding currents being 1·0 and 1·2 times the full-load current. The third set of curves were obtained under similar conditions to the second set, but with a 1 000 μF condenser connected across the single secondary resistance. This compensates to a great extent for the negative-sequence magnetizing current, and has the effect of increasing the half-speed and pull-out torques still further to 0·7 and 1·25 times the full-load value with little increase in current.

The addition of impedance in series with the secondary phases reduces the negative-sequence flux without appreciably affecting the positive-sequence flux. The secondary impedance should be resistive, since reactance, although giving the desired drop in voltage, contributes nothing to the output torque. The most economical way of introducing it is to insert resistances in series with two secondary phases whilst short-circuiting the datum phase. The upright of the central T of the equivalent circuit of Fig. 4 is then a negative resistance, as shown in Fig. 13(*a*). A more convenient circuit for computation is its symmetrical equivalent of Fig. 13(*b*), where all three resistances are equal and positive. The reduction of voltage required to avoid gross saturation is large; e.g. with the open-circuit characteristics of Fig. 11 and the normal phase voltage of 400 volts the negative-sequence e.m.f., V_2, must not exceed about 100 volts. This necessitates large external secondary resistances, and it has been found in practice that the dip in the torque/speed curve at one-half synchronous speed does not pass into the negative-torque

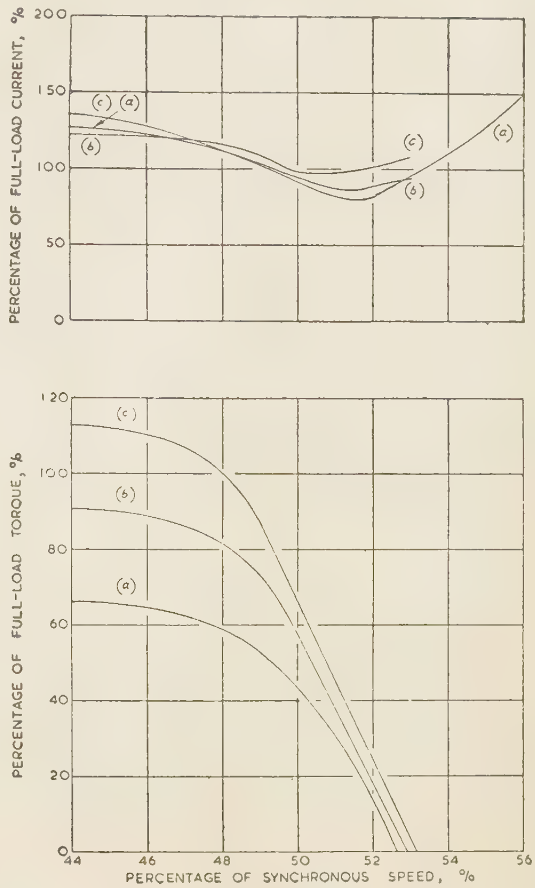

Fig. 12.—Experimental current/speed and torque/speed characteristics in the region of half normal speed, with a resistance in series with one secondary phase.

(*a*) Resistance of 20·2 ohms in series with one secondary phase and a phase voltage of $1/\sqrt{3}$ times the normal.
(*b*) Resistance of 57·4 ohms in series with one secondary phase and an inductive reactance of 6 ohms in series with each primary phase, the phase voltage being normal.
(*c*) As for (*b*), but with a 1 000 μF condenser in parallel with the one secondary resistance.

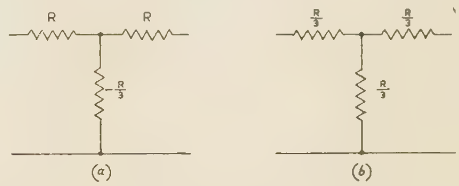

Fig. 13.—Positive–negative-sequence mutual impedance when equal resistances are connected in series with two secondary phases.

region (see Fig. 5A) so that stable reduced-speed operation at no load is impossible. However, stable operation can be obtained at higher loads, so that the method is applicable to cases where the reduced-speed load is always appreciable.

The practical advantages of these three methods may be summarized as follows: From the point of view of all-round technical efficiency the insertion of reactance into all three primary leads is the most effective method, star operation of a normally delta-connected machine being the next best, and the insertion of resistance in two secondary phases being the least flexible. On the score of cost and simplicity the order of cheapest to dearest is probably, delta-star switching, secondary resistance and primary reactance, particularly when a star-delta switch is already available.

The fourth method of eliminating magnetic saturation, i.e. by increase in the frame size, is attractive where improved half-speed performance is desired. An increase in machine dimensions of 13%, allowing an increase in turns per phase of 28% and an increase in pole area of 28%, allows the normal flux density to be reduced from 100 to 61%. This should be sufficient in all cases to give reasonable magnetizing currents when operating at full voltage with one secondary phase open-circuited.

(5.7) Vibration

The interaction of the positive-sequence m.m.f. with the negative-sequence flux, and the negative-sequence m.m.f. with the positive-sequence flux, produce torques which alternate at the relative slip frequency of the two components, and have zero mean value. These torques are responsible for the vibration in machines carrying unsymmetrical currents. Each of the two alternating torques is proportional to the product of the amplitudes of the flux and m.m.f. waves producing it, but since they alternate at the same frequency their resultant is the vector sum of the two components.

In this connection, the frequency of the alternating torque is $2sf_0$, and hence at one-half normal speed it is f_0, the supply frequency. When operating at exactly one-half synchronous speed the negative-sequence primary current is zero, so that the torque produced by the negative-sequence m.m.f. and positive-sequence flux is very nearly zero. On the machines tested, vibration in the region of one-half normal speed was not objectionable, being little more than when the machine is symmetrically loaded. However, the possibility of resonance with the mechanical load must be considered in any application.

(6) CONCLUSIONS

The operation of an induction motor at one-half its normal speed by means of unsymmetrical resistance in its secondary circuit is a practical possibility, but control of speed between one-half and the normal value is not possible by this means. The efficiency of such a machine is higher than that of a similar motor constrained to run at an equal speed by means of additional symmetrical resistance in its secondary circuit. It increases with increased asymmetry of the secondary impedance. The efficiency, when one secondary phase is open-circuited, is of the same order as that obtained with normal symmetrical operation. The output torque is limited by saturation of the main magnetic circuit of the machine to a continuous maximum of about 0·6–0·7 times the normal rated value, with somewhat higher torques available for short periods. If conditions require it, the torque can be doubled by an increase of about 13% in the machine dimensions. The machine will start satisfactorily against normal loads, but a speed reduction from normal to one-half may prove impossible unless the machine carries an appreciable load. The internal loss per unit of output torque is of the same order as that normally obtained, but since the loss in the secondary circuit is not symmetrically distributed amongst the phases, some derating must be applied.

Objection may be made to the method on the grounds of magnetic saturation, injection of low-frequency currents into the supply system and mechanical vibration, but simple means are available for overcoming these. To reduce magnetic saturation to a reasonable level with a minimum of additional equipment, the machine can be operated with its primary circuit star-connected if normally delta-connected, or reactance can be connected in series with the primary, or resistance can be connected in series with two secondary phases instead of the normal one. In the latter case it may not be possible to operate the machine at half speed when on no-load. Alternatively, the dimensions of the machine can be increased slightly with an all-round improvement in performance. Low-frequency injection into the supply and vibration can be reduced to negligible proportions by operating at speeds very close to one-half synchronous speed, and this can be done by choice of a suitable secondary unbalanced resistance.

The application of this method of speed reduction must be decided, as must that of any specialized method, on the merits of each particular case. Its advantages are its simplicity of connection and efficiency of operation, and its disadvantages are the necessity to avoid magnetic saturation and the presence of negative-sequence currents in the supply system. In addition to the 2-speed application, it provides a cheap and simple method of modifying an existing machine to run at one-half its normal speed. This modification may be applied to a squirrel cage motor by removing one-third of the bars under each pole or by replacing them with high-resistance bars.

(7) ACKNOWLEDGMENTS

The authors wish to thank the University of Sheffield for the experimental facilities provided, and they express their thanks to Mr. O. I. Butler for his advice and encouragement.

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(9) APPENDICES

(9.1) Symmetrical Components of Impedance

The symmetrical components of a set of three star-connected impedances Z_r, Z_y and Z_b are a convenient mathematical concept, and are defined in the same way as those of voltage and current:

$$Z_0 = \tfrac{1}{3}(Z_r + Z_y + Z_b)$$
$$Z_1 = \tfrac{1}{3}(Z_r + aZ_y + a^2Z_b)$$
$$Z_2 = \tfrac{1}{3}(Z_r + a^2Z_y + aZ_b)$$

It can be shown[3] that the symmetrical components of the currents flowing into the impedances and the symmetrical components of the voltages producing them are related by

$$V_0 = Z_0I_0 + Z_2I_1 + Z_1I_2$$
$$V_1 = Z_1I_0 + Z_0I_1 + Z_2I_2$$
$$V_2 = Z_2I_0 + Z_1I_1 + Z_0I_2$$

In the particular case considered, it is assumed for convenience that the negative-sequence voltage is initially generated by the flow of positive-sequence current in the unsymmetrical impedance, and the negative-sequence current produced by this voltage flows out of the impedance. Also it is assumed that the star points are isolated, so that I_0 is zero.

Hence

$$V_{c1} = V_1, \text{ but } V_{c2} = -V_2$$

and $I_{c1} = I_1$, but $I_{c2} = -I_2$

so that

$$V_{c0} = I_{c1}Z_2 - I_{c2}Z_1$$
$$V_{c1} = I_{c1}Z_0 - I_{c2}Z_2$$
$$V_{c2} = -I_{c1}Z_1 + I_{c2}Z_0$$

(9.2) Secondary Resistance for Exact Half-Speed Operation

At half speed, the resistance $R_a/(2s - 1)$ producing negative-sequence torque becomes infinite. Thus, neglecting magnetizing impedances, the positive-sequence current per phase is

$$I_1 = \frac{V_1}{\left[\left(R_a + 2R_c + \frac{2R'_c}{3}\right)^2 + (X_a + X_c)^2\right]^{\frac{1}{2}}}$$

where R'_c is the external secondary resistance referred to the primary circuit.

The current having thus been calculated, the positive-sequence torque per phase is $I_1^2(2R_c + \frac{2}{3}R'_c)$, the negative-sequence current and torque being zero.

If the torque required at half speed is known, it is simple to calculate the external secondary resistance R'_c to produce that torque.

DISCUSSION ON "THE CONTROL OF A THERMAL NEUTRON REACTOR"*

NORTH STAFFORDSHIRE SUB-CENTRE, AT STAFFORD, 26TH OCTOBER, 1953

Mr. W. E. Scott: In some cases it seems that data obtained from measurements on B.E.P.O. are extrapolated too far in the assumptions concerned with a reactor for reasonable electrical power output.

I think that it would be worth while, even at this stage, to consider the overall design of the control system for the production of electrical power. The characteristics of the steam-turbine–generator combination are now fairly well known, and since one source of disturbance to the overall system is at the electrical output, an estimate is necessary of the stability of performance as a whole. This is outside the scope of the paper, but the author's comments would be appreciated.

It would appear that the sets of rods for control and regulation could be replaced by one set. In view of the author's insistence on simplicity, there must be some good reason for the detailed specification of each, which is not immediately clear.

Although engineers are gradually becoming used to the idea of using electronic equipment, its use as the main detector of the energy level of the reactor seems to be a weak link in an otherwise strong chain. Is any effort being made to develop alternative methods?

Dr. J. P. Corbett: Having decided upon the type of control system required, a difficulty apparent from the paper is that of measuring the transfer function of the reactor itself. It is noted that the transfer function was developed from the measured harmonic response with the control system working in the closed-loop condition. This procedure is useful for purely investigational purposes, but some other method would obviously be required for the development of a control system preparatory to its manufacture.

Is it possible that, although the measurement of the response of the reactor to a sinusoidal forcing function is difficult, its response to a small step-increment of manual-control setting could be measured? If this could be done, a Fourier analysis could be carried out on the resulting characteristic so measured, and hence the transfer function of the reactor could be established.

Mr. R. V. Moore (*in reply*): In reply to Mr. Scott, the characteristics of nuclear reactors as understood from operating experiments with B.E.P.O. suggest that a nuclear power plant of the thermal-reactor type should be extremely stable in normal operation, even tending to be self-regulating at a predetermined power level. The periods of starting-up and shutting-down require careful consideration; the former leads to a rather slow starting process in the interest of plant safety, and the latter to the provision of a guaranteed cooling system to deal with residual heating from the reactor. These and other considerations lead to the decision to avoid, wherever possible, temporary reactor power fluctuations; and to this end it is envisaged that the nuclear power station would include an auxiliary condenser to which live steam could be diverted when the turbines for any reason could not accept the full steam load. It is agreed that the characteristics observed on B.E.P.O. may be modified by the higher temperatures and more intense nuclear reaction to be expected in power-producing reactors, but the understanding of B.E.P.O. characteristics constitutes a useful beginning.

With regard to the control and regulating rods, the function of the former is to compensate for large self-induced changes in reactivity which normally occur very slowly; whilst the latter allow small variations in reactivity to be produced quickly, which is a matter of convenience for power-level changing. The risk of dependence on electronic devices is minimized in practice by the evolution of simpler and more reliable equipment, sometimes replacing and sometimes augmenting more complicated circuits. An example of the latter is the provision of a power-measuring circuit consisting simply of an ionization chamber energized by a dry battery with indication on a microammeter.

In reply to Dr. Corbett, if a positive increment of reactivity is applied to a reactor in equilibrium its response is, to a first approximation, unbounded; i.e. the reaction increases without limit. Such a response is not amenable to Fourier analysis, since this requires that an integration over an infinite range of time shall converge to a limit. This mathematical difficulty does not, of course, deny the existence of a Fourier transform, which was indeed obtained by Mr. Ludbrook from step-function tests as described in his contribution to the London discussion.

* MOORE, R. V.: Paper No. 1431, January, 1953 (see **100**, Part I, p. 90).

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Paper No. 1758 M
Feb. 195

THE APPLICATION OF SYMMETRICAL COMPONENTS TO THE MEASUREMENT OF PHASE DIFFERENCE IN SINGLE-PHASE CIRCUITS

By R. L. RUSSELL, M.Sc., Associate Member.

(*The paper was first received* 8*th May, and in revised form*, 24*th August*, 1954.)

SUMMARY

The method described is a single-phase application of the general principle discussed in an earlier paper. In one application it gives directly the relative phase-displacement between any two comparable alternating voltages as the angular position of a linear trace relative to a uniformly graduated circular scale attached to the face of a cathode-ray tube. It is also possible to use a magslip, or an instrument of the ratiometer type, as an indicator in place of the cathode-ray tube.

The circuit arrangements employed are founded on symmetrical-component theory, which serves both as a basis for design and also for estimating the effect of conditions which are different from those the method ideally demands. Practical tests on the instrument and its circuits, which are exceptionally simple, are discussed.

(1) INTRODUCTION

For the measurement of relative phase-displacements between two electrical quantities at mains frequency and at ordinary power levels there is a wide range of commercially produced instruments from which to choose. At frequencies other than 50c/s at low power levels or, in general, under conditions widely different from those ordinarily encountered in industrial practice, phase-angle meters of orthodox design are not suitable, and numerous methods using a cathode-ray oscillograph have been devised. Those methods which depend on the geometrical properties of an ellipse are usually indirect and of doubtful practical value, and the others employ circuits and equipment of a complex kind.

The paper describes a method which is simple in principle and requires only a few standard components, and it gives the phase-displacement between the two single-phase electrical quantities as the angular setting of a straight-line trace, displayed against a circular scale attached to the face of a cathode-ray oscilloscope. The single-phase equipment here described is a particular practical application of a general principle discussed in an earlier paper,[1] which is the direct inverse of the well-known proposition which resolves a pulsating field into equal oppositely rotating components. Here, two rotating vectors are combined to give a single stationary pulsating vector, its position in space being determined by the relative phase difference between the separate generating vectors. Thus, the resultant of two rotating vectors $R_1 = \frac{1}{2}R\varepsilon^{-j\omega t}$ and $R_2 = \frac{1}{2}R\varepsilon^{j(\omega t+\phi)}$, with the same magnitude and angular frequency and opposed directions of rotation, is a vector $R\cos(\omega t + \frac{1}{2}\phi)\varepsilon^{j\frac{1}{2}\phi}$, which varies with time along an axis which is fixed in space in an angular position given by $\theta = \frac{1}{2}\phi$, where ϕ is the angle between R_1 and R_2 at $t = 0$.

This is illustrated geometrically in Fig. 1, in which one vector, R_1, rotates about a fixed point O and a second vector R_2 rotates about the extremity of the first. The locus of A_2 can be constructed in this way, somewhat tediously perhaps, in the most general case, but when $OA_1 = A_1A_2$ and the angular velocities are equal, it is clearly a straight line through O.

In terms of deflections on the cathode-ray oscillograph the rotating vectors referred to in the previous paragraph correspond

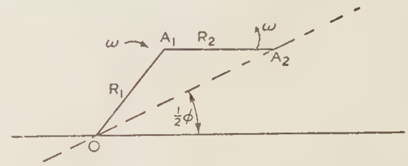

Fig. 1.—Showing that the locus of A_2, representing the resultant o two equal counter-rotating vectors R_1 and R_2, is a fixed straight line.

to circular traces. If two such traces can be combined, a linea trace corresponding to the line OA_2 in Fig. 1 will be produced

Single-phase and polyphase applications of this broad genera principle are markedly different in practice, and the latter ar simpler and more direct. The difference arises from the method and circuits which must be employed to produce, from tw single-phase sources, the two rotating fields actually, o effectively, required.

(2) PRINCIPLE OF MEASUREMENT

(2.1) General

It is clear from the argument outlined in the last Section that if two single-phase sources are to be the means of obtainin two rotating fields, established methods for producing circula traces on the cathode-ray tube cannot be used directly. Ordinarily each of the rotating vectors (Fig. 1) would be produced by tw pairs of deflector plates, and, unless a specially constructe deflector system is envisaged, other methods must be sought The mention of opposed rotating fields at once recalls th principles of symmetrical-component analysis; and it is b applying these principles that two counter-rotating vector system are obtained from two single-phase sources.

(2.2) Bi-phase (90°) Symmetrical Components

The fundamental theorem in symmetrical-component analysis, as often stated, is valid for any polyphase system, but it is em ployed almost exclusively in 3-phase systems and only infrequentl in other cases. It is the bi-phase (90°), or so-called 2-phase form which is required here. This is, more precisely, half bi-symmetrical 4-phase system containing no zero-sequenc component. In these terms, any two single-phase voltages V and V_2, regarded as an unbalanced bi-phase (90°) system, can b resolved into two balanced bi-phase (90°) systems of opposit phase rotation. By analogy with the more familiar 3-phas relations, or otherwise, the reference vectors V_{a1} and V_{a2} in th positive- and negative-sequence systems respectively are given b

$$V_{a1} = \tfrac{1}{2}(V_1 + jV_2), \quad V_{a2} = \tfrac{1}{2}(V_1 - jV_2) \quad . \quad . \quad (1$$

In particular, it follows from this last result that for all value of phase-displacement ϕ between V_1 and V_2, providing that the are equal in magnitude, V_{a1} and V_{a2} are in phase quadrature Furthermore, from the expressions

$$\left.\begin{aligned} V_{a1} &= V_1\cos(\tfrac{1}{2}\phi + \tfrac{1}{4}\pi)\varepsilon^{j(\frac{1}{2}\phi+\frac{1}{4}\pi)} \\ V_{a2} &= (-j)(V_1)\sin(\tfrac{1}{2}\phi + \tfrac{1}{4}\pi)\varepsilon^{j(\frac{1}{2}\phi+\frac{1}{4}\pi)} \end{aligned}\right\} \quad . \quad (2$$

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.

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n Section 9.1, it follows that the quotient of their magnitudes tan $(\frac{1}{2}\phi + \frac{1}{4}\pi)$ and from a knowledge of this, ϕ can be deduced. lternatively, by applying V_{a1} to the X-plates of a cathode-ray scillograph, and V_{a2} advanced in phase by $\frac{1}{2}\pi$—providing it can onveniently be done—to the Y-plates, a linear trace will be btained. From the inclination of this line to the horizontal, $\frac{1}{2}\phi + \frac{1}{4}\pi$), the phase angle ϕ can be found directly. It is not ssential to use electrostatic deflection, and simple magnetic eflecting coils at right angles to one another can equally well e employed.

In order to measure V_{a1} and V_{a2}, a number of circuits are vailable for the simultaneous measurement of positive- and egative-sequence components. A surprising property of such equence-selective circuits, to which the author has yet to find n exception for either 2- or 3-phase forms,[3] is that, whilst the neasured quantities are correct in magnitude, the phase angle etween them differs from that actually existing between the eference vectors V_{a1} and V_{a2} in the two component systems. his difference is constant and equal to the characteristic angle 2π/number of phases); that is $\frac{1}{2}\pi$ in the present instance, which , strictly, half a 4-phase system. When V_1 and V_2 are equal in nagnitude and it is known, therefore, that V_{a1} and V_{a2} are in uadrature, the effect of this unexpected additional phase-shift f $\frac{1}{2}\pi$ is that the measured quantities are exactly in phase, thus chieving in a simple manner, without the aid of special phase-hifting equipment, the precise conditions required for the athode-ray-oscillograph display.

(3) BI-PHASE (90°) SYMMETRICAL-COMPONENT BRIDGE: CIRCUIT RELATIONS

Of the possible circuits which might be employed, the one hown in Fig. 2 would not perhaps be selected first, but it is

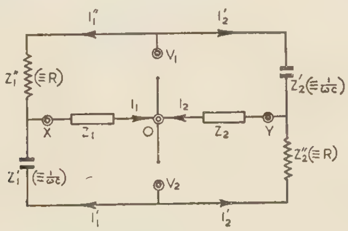

Fig. 2.—Four-element bridge

$R = Z_1'' = Z_2'' = 1\,400$ ohms; $Z_1' = Z_2' = 1/\omega C$: $C = 2{\cdot}275$ µF, at 50c/s. $V_1 = V_2 = 40$ volts. Z_1 and Z_2 are equal load impedances.

ound in practice to possess many desirable features not shared, or example, by the apparently simpler bridge described in ection 5.

In its most convenient practical form the bridge consists mply of two resistors R and two capacitors C each of which as the same numerical impedance, and the load impedances X and OY must be identical, but the actual value is not nportant. Regarding the applied voltages V_1 and V_2 as members f an unbalanced bi-phase (90°) system, the voltages V_{OX} and V_{OY} can be expressed in terms of the positive- and negative-equence components V_{a1} and V_{a2} respectively, the resistance R nd load impedance $Z (= Z_1 = Z_2)$, as shown in Section 9.2

$$V_{OX} = \frac{2V_{a1}}{(1+j) + R/Z}, \quad V_{OY} = \frac{j(2V_{a2})}{(1+j) + R/Z} \quad . \quad (3)$$

It will be observed that V_{OY} is displaced by $\frac{1}{2}\pi$ from V_{a2} (see ection 2.2). In the particular case when V_1 and V_2 are umerically equal in magnitude, these expressions can be written

$$\left.\begin{aligned} V_{OX} &= \frac{(\sqrt{2})V_1 \cos(\frac{1}{2}\phi + \frac{1}{4}\pi)\varepsilon^{j\frac{1}{2}\phi}}{1 + \dfrac{R(1-j)}{2Z}} \\ V_{OY} &= \frac{(\sqrt{2})V_1 \sin(\frac{1}{2}\phi + \frac{1}{4}\pi)\varepsilon^{j\frac{1}{2}\phi}}{1 + \dfrac{R(1-j)}{2Z}} \end{aligned}\right\} \quad . \quad . \quad . \quad (4)$$

Thus the voltages are in phase in time and proportional to the cosine and sine respectively of half the displacement between V_1 and V_2 (see Section 9.2).

It follows that either identical magnetic deflector coils, set at right angles on the neck of the cathode-ray tube, or the ordinary electrostatic deflector plates, with matched sensitivities as later discussed, may be connected between OX and OY to produce a linear trace for determining ϕ directly. The smaller the ratio R/Z, the less its effect in the above expressions, and, when electrostatic deflections are employed, it can be neglected, except at very high frequencies. Then

$$\left.\begin{aligned} V_{OX} &= (\sqrt{2})V_1 \cos(\tfrac{1}{2}\phi + \tfrac{1}{4}\pi)\angle\tfrac{1}{2}\phi \\ V_{OY} &= (\sqrt{2})V_1 \sin(\tfrac{1}{2}\phi + \tfrac{1}{4}\pi)\angle\tfrac{1}{2}\phi \end{aligned}\right\} \quad . \quad . \quad . \quad (5)$$

The vector diagram is shown in Fig. 3. As ϕ varies, the point O effectively takes different positions along XY, and the values of OX and OY are easily shown to be consistent with those given by eqns. (5) above.

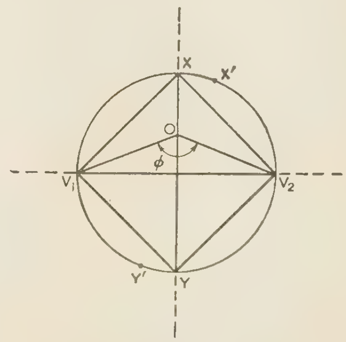

Fig. 3.—Vector diagram of 4-element bridge.

$OV_1 \equiv V_1$, $OV_2 \equiv V_2$. $OX = (\sqrt{2})V \cos(\frac{1}{2}\phi + \frac{1}{4}\pi)$. $OY = (\sqrt{2})V \sin(\frac{1}{2}\phi + \frac{1}{4}\pi)$ when $|V_1| = |V_2| = V$.

(4) THE BRIDGE AS A MEASURING DEVICE

(4.1) Tests on Bridge Circuit

The bridge circuit was assembled from matched components of ordinary commercial quality and terminals X, Y, V_1, V_2 and O, as shown schematically in Fig. 2, were mounted on the front panel. In ordinary use, test voltages V_1 and V_2 are connected between terminals marked O and V_1, and O and V_2, respectively, and output voltages given by eqns. (5) appear between O and X, and O and Y respectively.

The performance of the bridge can be tested independently of the direct-reading indicating-device finally employed, with an accuracy which is limited only by the accuracy of the voltmeters used to measure V_{OX} and V_{OY}, and hence to determine their ratio (Section 2.2). An experimental graph can be drawn showing the error between predetermined values of the phase displacement between voltages V_1 and V_2, and corresponding values calculated from measured values of V_{OX} and V_{OY}. The error for the greater part is less than 1° and the deviations are of a random kind in magnitude and sign, and probably due to fluctuations in the supply.

(4.2) Methods of Indicating the Bridge Output Voltages and Test Results

There are a number of ways in which the bridge output voltages can be employed to give a direct indication, and it is most convenient that any indicating device to be used can be tested separately before insertion in the bridge circuit, simply by applying to it two co-phasal voltages derived from the same single-phase source and adjusted to have amplitudes proportional to $\cos(\frac{1}{2}\phi + \frac{1}{4}\pi)$ and $\sin(\frac{1}{2}\phi + \frac{1}{4}\pi)$, as eqns. (5) demand, for a range of values of ϕ. One of the stator coils of a 2-phase instrument of the magslip type, for example, can be connected between O and X, and the other between O and Y. The unenergized H-shaped rotor then aligns itself with the resultant field, whose position is determined by the phase displacement ϕ, which can be read directly from a uniformly graduated circular scale. The maximum error found in this way was less than 2° but greater than that obtained from the bridge alone, using voltmeters as described above. Separate tests showed that this reflected to some extent the known imperfections of the instrument, which had been adapted, and not specially designed, for the present application.

When a cathode-ray oscillograph was used as the indicating device, with the X- and Y-plates connected across OX and OY respectively, the trace produced was constant in length and for the most part linear, but for some values of ϕ differed slightly from the straight line expected. The thin 3-looped figure then obtained was shown to be the effect of an appreciable third harmonic (4%) in the supply and was most pronounced for those values of ϕ for which either V_{OX} or V_{OY} should ideally be zero. The harmonic voltage is not simultaneously zero and produces deviations at triple frequency about the vertical or horizontal line which would be obtained if it were not present. The error is less than 2°.

It is important to ensure that the effective sensitivities of both pairs of deflector plates are the same, and, to avoid undesirable phase-shifts, this is best achieved by arranging for the most sensitive pair to form one member of a preset capacitance potential-divider. The shunting resistor sometimes connected across the deflector plates should be removed, and the cathode-ray tube selected should be one in which the X- and Y-deflections are, in fact, perpendicular, as experience has shown that they sometimes differ by as much as 5° from quadrature.

(4.3) Bridge Adjustment

With the X- and Y-plates of the oscillograph connected as already described in Section 4.2, the procedure for adjusting the bridge is to connect a single-phase supply of the required frequency between X and Y (Fig. 2), to short-circuit terminals O and V_2, leaving OV_1 on open circuit, and to adjust the capacitor Z_1' until the elliptical trace observed becomes a circle. This can conveniently be done by comparing the trace obtained with the circles on the transparent polar-co-ordinate scale which is also employed for reading the phase angle.

A rotary selector switch enables the test connections described in the last paragraph to be advanced to occupy each of the four possible bridge positions in turn, so that each component can be adjusted with respect to the one connected to it at either end, and the final setting obtained very accurately. This is probably the best method of presetting the bridge, as it is done under conditions very similar to those in which the bridge will be used and is accomplished easily and quickly in practice.

As a final check, or as an alternative method, when the single-phase supply between X and Y is removed and connected between O and V_1, OV_2 remaining on short-circuit, a circular trace should also be obtained. The selector switch enables the same supply to be transformed to OV_2, and OV_1 to be short-circuited when a circular trace with the same radius as before should be produced. The two circular paths are in fact traversed in opposite directions and, if the principle of oppositely rotating fields has been obscured, it is thus easily restored.

Without further modification the bridge will be suitable only for one particular frequency, namely that given by $R = 1/\omega C$. The effect of using the bridge at some other frequency corresponds to a rotation of the diameter XY in Fig. 3 to some other position X′Y′. The voltages OX′ and OY′ are not in phase, and the trace will be an ellipse instead of a line, but it is a simple matter to adjust either both the resistors or both the capacitors until a linear trace is obtained. The most convenient arrangement is to use two separate, similar, variable capacitors which have been correctly trimmed (using split end-plates normally provided for this purpose) and then mounted so that their spindles are rigidly coupled but not connected electrically. Because there must be no direct connection between them, ordinary ganged capacitors cannot be employed and care is required during construction if hand-capacitance effects are to be avoided.

The potential reference point O, common to the oscillograph and test voltages, permits simple and efficient screening, and so enables high frequencies or high-gain amplifiers to be used without the complication of auxiliary earthing or balancing circuits.

(4.4) Unequal Test Voltages

When the voltages V_1 and V_2 are unequal, the point O in Fig. 3 no longer lies on XY; and again, V_{OX} and V_{OY} will not be in phase and the trace will be an ellipse. The direction of the major axis of the ellipse is $(\frac{1}{2}\phi + \frac{1}{4}\pi)$ as for the ideal line, and ϕ can still be found but with diminished accuracy for large differences between V_1 and V_2, as shown in the earlier paper.[1] In such cases, variable potential-dividers can be placed between the test voltages and the bridge input terminals, and the setting varied until a line is obtained. Alternatively, variable-gain amplifiers could equally well be employed for this purpose in suitable circumstances.

(4.5) Effect of Harmonics

In general, whereas maladjustment of the bridge or inequality of the input voltages produces an ellipse, a characteristic long thin multi-looped figure reveals the presence of harmonics. The effect is complex but broadly predictable.[1] The transverse dimensions of the loops increase with the harmonic amplitude, and whilst the axis of the figure is determined substantially by the fundamental components, the accuracy with which it can conveniently be measured is diminished. With a clearly focused line of length about 5·0cm, a 2% harmonic can just be detected from the appearance of the trace. At worst, this might produce an error of 2° in the estimation of ϕ. Should the observed harmonic content be excessive, an obvious remedy would be to connect a resonant parallel circuit across the bridge input terminals.

(4.6) Special Features of Cathode-Ray Indicator

The advantages of the method, as used with the cathode-ray tube, can be summarized as follows:

(*a*) Its accuracy does not depend on the long-term stability of preset or calibrated components.

(*b*) Separate tests are not required to detect incorrect adjustments of the bridge components, or inequality or distortion of the test voltages, as these are revealed by the shape of the trace.

(*c*) The instrument is self-contained and can be adjusted or reset without reference to external standards and measurements.

(*d*) It is not necessarily a fixed-frequency device.

(4.7) Estimates of Comparative Accuracy

It has been estimated that a reliability of about 1 part in 5 000 can be achieved in *RC* networks,[4] but, without using components of standard or sub-standard accuracy, the test results obtained could be improved by using better-quality bridge components and a properly-designed indicating instrument with an extended pointer and possibly a vernier scale.

The residual errors obtained in the cathode-ray-tube application cannot be significantly reduced, as the position of the linear trace cannot be determined with an accuracy greater than about 1°. The results are none the less better than those achieved by direct-reading methods of comparable simplicity. Errors arising from the measurement of Lissajous figures[5] are variable with phase and may be 8° or more and, from geometrical measurements on an ellipse,[6] about 2·5°, and in any event these methods are indirect. Various electronic methods, some very complicated, have claimed accuracies within 1·0°, 0·75°, 0·5°, 0·25° and 0·1° (see References 7, 8, 9, 10 and 4 respectively).

(4.8) General

As the account in the preceding Sections might suggest, the particular circuits described are not the only ones which could be used. Subject to the conditions established in the Appendix, the circuits can be modified and impedances used instead of pure resistors and pure capacitors.

If greater variety is required, the duals, or reciprocals, of these circuits can be considered. In Section 5 is described Fortescue's bridge (Fig. 4) which, like Wheatstone's bridge of

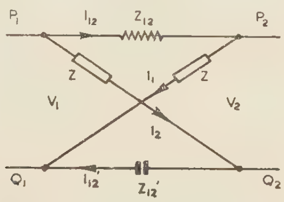

Fig. 4.—Bi-phase (90°) equivalent of Fortescue's bridge.

Z_{12} and Z_{12}' are bridge components. Z represents external load impedance.

the same type, is self-conjugate, but the reciprocal of Fig. 2 is of a different form and has been employed at low frequencies with magnetic deflector coils on a cathode-ray tube. Furthermore, there are other sequence-component circuits, in addition to those mentioned here, which could be considered.

(5) A 2-ELEMENT BRIDGE

In any account of sequence-component networks some explanation would be required for omitting the circuit shown in Fig. 4, which is the bi-phase (90°) equivalent of Fortescue's bridge.[2] In this circuit, when $|V_1| = |V_2|$ and the current in diagonal branches is negligibly small,

$$\left.\begin{aligned} V_{P_2Q_1} &= (\sqrt{2})V_1 \cos(\tfrac{1}{2}\phi + \tfrac{1}{4}\pi)\varepsilon^{j\frac{1}{2}\phi} \\ V_{P_1Q_2} &= (\sqrt{2})V_1 \sin(\tfrac{1}{2}\phi + \tfrac{1}{4}\pi)\varepsilon^{j\frac{1}{2}\phi} \end{aligned}\right\} \quad . \quad . \quad (6)$$

In principle, therefore, this circuit gives the required output voltages exactly as before (Section 9.3). In a particular application, input amplifiers to the bridge were used and the diagonal voltages given by eqns. (6) were also amplified before being applied to the X- and Y-plates of the cathode-ray oscillograph. The output amplifiers serve to isolate the deflector plates, which cannot be connected directly across the bridge diagonals in the usual way because of the common earth connection of the plates. For input voltages of 0·5 volt, a trace 5cm long was obtained for a frequency range 50–3 000c/s, but there was a deterioration in performance at higher frequencies. The circuit was inherently unsatisfactory, and the care required in design and adjustment of the amplifiers more than offset the apparent simplicity of the bridge itself. This was attributed primarily to the lack of a common reference potential between the two input voltages and the deflector plates of the cathode-ray oscillograph.

When identical finite impedances are connected between P_1Q_2 and P_2Q_1 the essential phase and magnitude eqns. (6) are disturbed, but they can be restored by suitably modifying the bridge circuit. A 2-phase magnetic-deflector system has been used in this way, but the circuit adjustments are tedious and complicated and could be done conveniently only at one particular frequency. In short, the chief merit of this circuit is economy of components, but it is not very suitable for this application.

(6) CONCLUSIONS

The earlier paper referred to[1] employed the principle of counter-rotating fields to produce an electric differential. This paper has applied the differential principle to single-phase circuits in a generalized way, using symmetrical-component methods. The analysis, being thus closely related to that already established specifically for asymmetrical conditions, enables performance under all circumstances to be predicted with unusual ease. It is thought to give a method of phase indication and measurement more accurate, in relation to its extreme simplicity, than others previously described.

Since this work has been completed, the author's attention has been drawn to two earlier papers,[12,13] both of which describe methods of producing a linear trace on the cathode-ray tube. Both methods are, however, much more complicated than those discussed here.

(7) ACKNOWLEDGMENTS

The work described in the paper was carried out in the Electrical Engineering Department of the University of Bristol. The author would like to acknowledge the facilities he has enjoyed, and to thank Messrs. N. W. Hodges, N. J. Brownsey and I. R. Smith, formerly Honours Students in this Department, for their assistance in the experimental tests.

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(9) APPENDIX

(9.1) A Theorem in Symmetrical Components

When V_1 and V_2 denote voltages of an unbalanced bi-phase (90°) system, it can be shown analytically, and verified easily by geometrical methods, that the positive and negative sequence components V_{a1} and V_{a2} are respectively given by

$$V_{a1} = \tfrac{1}{2}(V_1 + jV_2) \quad \text{and} \quad V_{a2} = \tfrac{1}{2}(V_1 - jV_2) \quad . \quad . \quad (7)$$

In the special case when $|V_1|$ and $|V_2|$ are equal, and V_2 is leading by an angle ϕ, V_2 can be eliminated from these equations. Putting $V_2 = V_1\varepsilon^{j\phi}$ and simplifying gives

$$\begin{aligned} V_{a1} &= \tfrac{1}{2}V_1(1 + j\cos\phi - \sin\phi) \\ &= \tfrac{1}{2}V_1(\cos\tfrac{1}{2}\phi - \sin\tfrac{1}{2}\phi)[(\cos\tfrac{1}{2}\phi - \sin\tfrac{1}{2}\phi) \\ &\quad + j(\cos\tfrac{1}{2}\phi + \sin\tfrac{1}{2}\phi)] = V_1\cos(\tfrac{1}{2}\phi + \tfrac{1}{4}\pi)\varepsilon^{j(\frac{1}{2}\phi+\frac{1}{4}\pi)} \quad . \quad (8) \end{aligned}$$

$$\begin{aligned} V_{a2} &= \tfrac{1}{2}V_1(1 - j\cos\phi + \sin\phi) \\ &= (-j)V_1\sin(\tfrac{1}{2}\phi + \tfrac{1}{4}\pi)\varepsilon^{j(\frac{1}{2}\phi+\frac{1}{4}\pi)} \quad . \quad (9) \end{aligned}$$

The operational terms in eqns. (8) and (9) are the same except for a factor $(-j)$, showing that V_{a1} and V_{a2} are always in quadrature for all values of ϕ. The magnitudes of V_{a1} and V_{a2}, however, vary with phase displacement and are proportional to the cosine and sine respectively of $(\frac{1}{2}\phi + \frac{1}{4}\pi)$ so that ϕ can be determined from a knowledge of their ratio.

(9.2) Analysis of 4-element Bridge

For analytical purposes, generalized branch impedances, $Z_1, Z_1', Z_2 \ldots$, will be employed, at least in the first instance, in place of the resistors and capacitors shown in Fig. 2, which represents the simplest but not the only possible circuit.

Writing down Kirchhoff's laws foı one half of the circuit and eliminating $(I_1 + I_1')$,

$$V_1Z_1' + V_2Z_1'' = I_1(Z_1'Z_1'' + Z_1Z_1' + Z_1''Z_1) \quad . \quad (10)$$

and for the other half of the circuit, eliminating $(I_2 + I_2')$,

$$V_1Z_2'' + V_2Z_2' = I_2(Z_2'Z_2'' + Z_2Z_2' + Z_2''Z_2) \quad . \quad (11)$$

From eqns. (7), (10) and (11), it is sufficient, if I_1 and I_2 are to be proportional to V_{a1} and V_{a2} respectively, that $Z_1'' = jZ_1'$ and $Z_2' = -jZ_2''$; but when, in addition, the constants of proportionality are required to be the same, then $Z_1'' = Z_2''$ and therefore $Z_1' = Z_2'$, and $Z_1 = Z_2$.

$$I_1 = \frac{2V_{a1}}{Z_1'' + Z_1(1 + j)} \quad I_2 = \frac{(j)2V_{a2}}{Z_2'' + Z_2(1 + j)} \quad . \quad (12)$$

The simplest way of satisfying these relations is to use resistors and capacitors as shown in Fig. 2, but a pure reactance is not essential as the quadrature conditions can be met in more genera cases.

A peculiar characteristic of this circuit and others of its typ is the additional constant phase-shift $(\frac{1}{2}\pi)$ which is introduced i the currents I_1 and I_2 as shown by eqn. (12). It would not b true to say that the applications described depend wholly on fortunate combination of the last result and that of Section 9.: but without it, the form the circuits would take in practice woul be much less simple.

When equal impedances of a sufficiently high value compare with the branch impedances, e.g. deflector plates of the cathode ray oscillograph, are connected between OX and OY, th voltages across them, I_1Z_1 and I_2Z_2 respectively, are, fror eqn. (12):

$$\left.\begin{aligned} V_{OX} &= (\sqrt{2})V_{a1}\left(\frac{1-j}{\sqrt{2}}\right) = (\sqrt{2})\overline{\backslash 45^\circ}\, V_{a1} \\ V_{OY} &= (j)(\sqrt{2})V_{a2}\left(\frac{1-j}{\sqrt{2}}\right) = j(\sqrt{2})\overline{\backslash 45^\circ}\, V_{a2} \end{aligned}\right\} \quad . \quad (13$$

From eqns. (7), (8) and (9),

$$\left.\begin{aligned} V_{OX} &= (\sqrt{2})V_1\cos(\tfrac{1}{2}\phi + \tfrac{1}{4}\pi)\varepsilon^{j\phi/2} \\ V_{OY} &= (\sqrt{2})V_1\sin(\tfrac{1}{2}\phi + \tfrac{1}{4}\pi)\varepsilon^{j\phi/2} \end{aligned}\right\} \quad . \quad . \quad . \quad (14$$

(9.3) Bi-phase Equivalent of Fortescue's Bridge

In much the same way as in Section 9.2, expressions for I and I_2 can be obtained by writing down Kirchhoff's laws for th circuit shown in Fig. 4 and eliminating I_{12} and I_{12}'. In general,

$$I_1 = \frac{V_1(Z_{12}')(Z + Z_{12}) + V_2(Z_{12})(Z + Z_{12}')}{Z[Z_{12}'(Z_{12} + Z) + Z_{12}(Z_{12}' + Z)]} \quad . \quad (15$$

$$I_2 = \frac{V_1(Z_{12})(Z + Z_{12}') + V_2(Z_{12}')(Z + Z_{12})}{Z[Z_{12}'(Z_{12} + Z) + Z_{12}(Z_{12}' + Z)]} \quad . \quad (16$$

For I_1 and I_2 to be proportional to the positive- and negative sequence components, $Z_{12}(Z + Z_{12}') = jZ_{12}'(Z + Z_{12})$, and th above expressions then reduce to

$$I_1 = \frac{2V_{a1}}{Z(1+j)}, \quad I_2 = \frac{j2V_{a2}}{Z(1+j)} \quad . \quad . \quad . \quad (17$$

Again, the phase displacement between I_1 and I_2 exceeds tha between V_{a1} and V_{a2}, to which they correspond, by a constar value $\frac{1}{2}\pi$.

From eqns. (8) and (9),

$$\left.\begin{aligned} V_{P_2Q_1} &= (\sqrt{2})V_1\cos(\tfrac{1}{2}\phi + \tfrac{1}{4}\pi)\varepsilon^{j\frac{1}{2}\phi} \\ V_{P_1Q_2} &= (\sqrt{2})V_1\sin(\tfrac{1}{2}\phi + \tfrac{1}{4}\pi)\varepsilon^{j\frac{1}{2}\phi} \end{aligned}\right\} \quad . \quad . \quad (18$$

The required relation between the bridge component established above, can be written as

$$\left(\frac{1}{Z_{12}} + \frac{1}{Z}\right) = j\left(\frac{1}{Z} + \frac{1}{Z_{12}'}\right) \quad \text{or} \quad g_\alpha = jg_\beta$$

To adjust an admittance g_α to be in quadrature with an admittanc g_β is not impossible but is tedious in practice. When, howeve $1/Z$ can be neglected, as, for example, when deflector plates c the oscillograph are connected across the diagonals, the cor dition reduces to $Z_{12}' = jZ_{12}$, which is most easily satisfied if Z_1 is a pure resistance, Z_{12}' a pure capacitance and $R = 1/\omega C$.

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Feb. 1955

THE DETERMINATION OF PHASE ROTATION OF POLYPHASE SYSTEMS

By R. L. RUSSELL, M.Sc., Associate Member.

(*The paper was first received* 24*th August and in revised form* 18*th November*, 1954.)

SUMMARY

The device described, with test results, depends on symmetrical-omponent principles and consists of two neon tubes in a very simple reset bridge circuit. The phase rotation is shown by the lighting of ne of the lamps, the other remaining unlit, and the instrument is uperior in this respect to the traditional Varley method, in which either lamp is ordinarily completely extinguished. Wide variations f applied voltage are permissible, and a positive indication continues o be given for wider changes in frequency, and for systems which are nore unbalanced, than will be encountered in ordinary industrial ractice or could be used with orthodox induction-type indicators.

The instrument, in effect, determines the relative phase-displacement f the two voltages applied to it and has been used in a more precise orm as a phase-angle meter. Only two voltages of the supply system re therefore required, either line or phase values, and satisfactory erformance is achieved in practice for polyphase systems for which the evice was not specifically designed. The power consumption is small.

LIST OF SYMBOLS

V_A, V_B = Reference and succeeding voltages respectively of a polyphase system.

V_{OX}, V_{OY} = Bridge output voltages numerically equal, or proportional, to the positive-sequence and negative-sequence components respectively.

V_S = Neon-tube striking voltage.

V_{a1}, V_{b1}, V_{c1} = Positive-sequence components of an unbalanced 3-phase system.

V_{a2}, V_{b2}, V_{c2} = Negative-sequence components of an unbalanced 3-phase system.

V_3, V_5, V_7 = R.M.S. values of 3rd, 5th and 7th harmonic components respectively.

(1) INTRODUCTION

The expression "phase sequence" is one which is quite familiar n electrical terminology and whose meaning is never in doubt; ut exactly what is meant by a phase-sequence indicator or a hase-sequence meter is, out of context, not so clear. The ormer is usually taken to be a device which has been designed pecifically to determine the phase rotation of a 3-phase supply; ne latter may be an instrument for measuring the magnitudes of ne sequence components in an unbalanced system. Whereas ne is an accurate instrument, not perhaps in great demand, the ther is not a precision device, and the forms they take in practice re usually quite different. They are not, however, as unrelated n principle as they appear to have been regarded hitherto.

A knowledge of phase rotation is regularly required in elecrical installation practice, and recent publications[1,2] have evived interest in this topic. They have, however, been content o discuss detailed improvements to the familiar Varley circuit rst described almost forty years ago. The essentials of the resent method were contained implicitly in an earlier paper[3] nd more specifically in practical form in the preceding paper ee page 80).

Written contributions on papers published without being read at meetings are vited for consideration with a view to publication.

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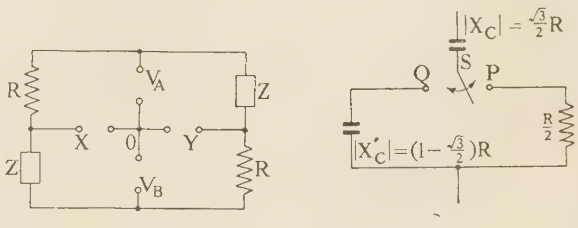
(2) METHOD

(2.1) General Principle

The fundamental symmetrical-component theorem states that any unbalanced 3-phase system is composed of two balanced 3-phase systems of opposed phase sequence, the positive- and negative-sequence systems, and a zero-sequence system. Corresponding to this analysis, there exist a number of practical methods for selecting these components and measuring them separately. Clearly, if an exactly balanced 3-phase voltage supply with conventional phase rotation is applied to a circuit designed to respond to the positive-sequence component only, the reading obtained will simply be proportional to the applied voltage. Merely reversing the phase rotation of the balanced supply, by interchanging any two of the three leads in the usual way, will convert it to a purely negative-sequence system, and the corresponding meter deflection will therefore be zero. A meter in a negative-sequence measuring circuit, on the other hand, would be deflected in the second case and not in the first. In both cases an unambiguous indication of the phase rotation of the applied voltage system is thus obtained. Indeed, methods of this kind have been employed to provide a critical test of the accuracy of adjustment of circuit components when assembling the sequence-selective circuits themselves, but that they can be used conversely to determine the phase rotation does not appear to have been observed.

As the symmetrical principles employed have been devised specifically for the analysis of unbalanced systems, a further advantage is that established methods are available for estimating the behaviour in practice when conditions can only be regarded as good approximations to those ideally presumed above. When the voltage system is not exactly balanced, for example, neither of the sequence components will be zero, but that which is by far the larger of the two determines the phase sequence as before. It is convenient, therefore, to use circuits which respond to both the positive- and negative-sequence components simultaneously. These are usually *RC* or *RL* networks, and the circuit of one of them is shown in Fig. 1(*a*). It is discussed in greater detail in the preceding paper. A quite simple modification to the basic



(*a*) (*b*)

Fig. 1.—Phase sequence selective circuit.

(*a*) Schematic.
V_A and V_B are reference and succeeding vectors respectively in the applied voltage system. The positive-sequence component voltage is established across OX; the negative-sequence component across OY.
(*b*) Circuit and switching arrangements, for each of the impedances Z in Fig. 1(*a*), for a combined 3-phase and bi-phase (90°) network. With change-over switch S on P, the 3-phase condition $R = -a^2Z$ is satisfied; with S on Q, the bi-phase relation $R = jZ$ is obtained.

circuit, with the addition of a selector switch for choosing the required value of Z, enables one network to be converted to either the 3-phase or the bi-phase (90°) form. The detailed arrangement of the identical branch impedances Z in Fig. 1(*a*), in this combined circuit, is shown in Fig. 1(*b*).

(2.2) Circuit Details

Two meters could be employed in Fig. 1(*a*), one for measuring the positive sequence voltage V_{OX} and the other for the negative sequence voltage V_{OY} or, with suitable switching arrangements, one only would be sufficient. It is thought, however, that it is inappropriate to use precision instruments when the problem is to determine which of two usually quite different voltages is the larger, and that indicator lamps, as in the traditional Varley method, are both economical and adequate for the purpose, except possibly at the limit of the performance range.

Neon tubes, with additional ballast resistors, are preferred to tungsten lamps, both for their low power consumption and the greater voltage range over which they can be used. For low-voltage systems, e.g. those less than 100 volts, transformers are required to step up the voltage to a value exceeding the striking voltage of the neon tubes used. This is not a serious disadvantage, as the transformers need be of low rating only, and would rarely be required in industrial applications.

In both the 3-phase and the bi-phase (90°) forms of Fig. 1(*a*), the four arms all have the same numerical impedance, but in the former case $R = -a^2Z$ and in the latter $R = jZ$, where a and j are the 120° and 90° operators respectively. For given values of R, the condition $R = jZ$ in one case defines a capacitive reactance given by $R = X_c$, and in the other the 60° impedance required is simply a resistance $\frac{1}{2}R$ in series with a capacitance so chosen that $X_c = \frac{1}{2}\sqrt{(3)}R$. A ganged switch S, one half of which is shown in Fig. 1(*b*), allows the appropriate value of Z to be selected for either the 3-phase or the bi-phase (90°) forms.

The output voltages of the bridge network when the impedances between O and X, and O and Y are high are given as follows:

(*a*) 3-*phase case*:

$$V_{OX} = \frac{1}{\sqrt{3}}[V_A - a^2V_B] = \text{magnitude of positive-sequence component}$$

$$V_{OY} = \frac{1}{\sqrt{3}}[V_A - aV_B] = \text{magnitude of negative-sequence component}$$

(*b*) *Bi-phase* (90°) *case*:

$$V_{OX} = \frac{1}{\sqrt{2}}[V_A - j^3V_B] = \sqrt{2}\ \text{(magnitude of positive-sequence component)}$$

$$V_{OY} = \frac{1}{\sqrt{2}}[V_A - jV_B] = \sqrt{2}\ \text{(magnitude of negative-sequence component)}$$

where V_A and V_B are two consecutive voltages derived from the system whose phase sequence is required.

(3) PRACTICAL TESTS

(3.1) Unbalanced Voltage Systems

When, in the 3-phase form of Fig. 1(*a*), V_B is exactly equal to V_A and lags by precisely $\frac{2}{3}\pi$, V_{OX} is proportional to V_A and V_{OY} is zero. Providing that V_{OX} then exceeds the neon-tube ionizing voltage, the lamp across OX will strike and the other will remain dark, indicating the phase rotation V_A—V_B—V_C. Alternatively, the phase rotation is shown to be V_A—V_C—V_B when the neon tube across OY is bright and the one across OX fails to strike. When, however, V_A and V_B are members of an unbalanced system, as strictly they will be to a lesser or greater extent in practice, both neon tubes will have a voltage applied to them—the positive-sequence component in one case and the negative-sequence component in the other. The general effect of unbalance is predictable theoretically and can be illustrated in simple graphical form.

The magnitude of the positive-sequence component of an unbalanced 3-phase system, containing no zero-sequence component, is $1/\sqrt{3}$ times the resultant of one of the voltage vectors minus the succeeding vector retarded in phase by $\frac{2}{3}\pi$. In a similar way, the negative-sequence component is the vector difference between one voltage vector and the succeeding vector advanced in phase by $\frac{2}{3}\pi$, divided by $\sqrt{3}$. Thus, if DO in Fig. 2 is drawn vertically to represent V_A and DE corresponds

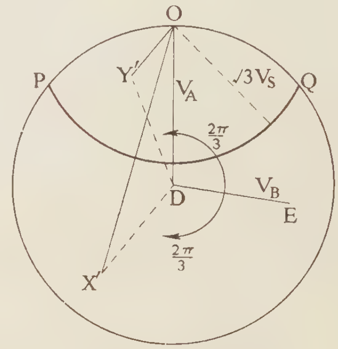
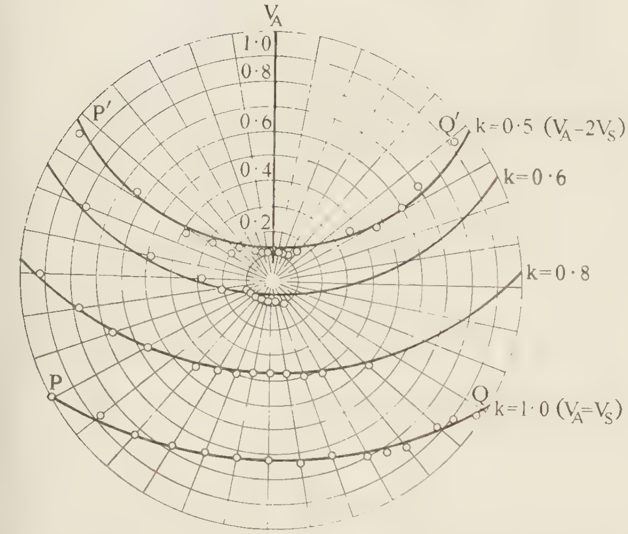


Fig. 2.—Geometrical construction for finding the values of V_{OX} and V_{OY} in the 3-phase form of Fig. 1(*a*).

to either of the other two voltages, say V_B, in magnitude and correct relative phase ($V_A \geqslant V_B$), the sequence components are numerically equal to $OX'/\sqrt{3}$ and $OY'/\sqrt{3}$, where DY′ and DX′ are both equal to DE but displaced $\frac{2}{3}\pi$ with respect to it as shown. When OX′ is greater than OY′, V_B is a lagging vector with respect to V_A, and when OY′ exceeds OX′, V_B is a leading vector. The particular case when OX′ and OY′ are equal is not relevant as it corresponds to V_A and V_B being either in phase or 180° out of phase.

Denoting the striking voltages of the neon tubes by V_S, the conditions for one to be bright and the other dark is $V_{OX} > V_S > V_{OY}$ or, of course, $V_{OX} < V_S < V_{OY}$. Graphically, from Section 2.2, X′ and Y′ must be on opposite sides of the arc of a circle PQ, of radius $\sqrt{3}V_S$ and centre O. Limiting conditions occur when either X′ or Y′, or both, lie on the circular arc, and thus an estimate can be made of the variation in magnitude and relative phase of V_B which can be permitted for a particular value of V_A and V_S.

It is possible to avoid constructing a separate diagram for each value of system voltage and striking voltage, as is strictly required, by taking OD ($\equiv V_A$) of fixed length and expressing all other quantities as fractions of V_A. Fig. 3 is an extended form of Fig. 2 developed in this way; circular arcs corresponding to PQ are obtained for different values of V_S. Alternatively, when V_A is regarded as variable, the scale of the diagram is in effect different for each system voltage; therefore a constant value of V_S will correspond to a different length in each, and a system of circular arcs, centre O and radius $\sqrt{3}(V_S/V_A)$(OD) replaces the single limiting arc PQ in Fig. 2. As the experimental values plotted in Fig. 3 will show, there is a surprisingly close agreement with critical curves deduced theoretically. It is equally satisfactory that a clear unambiguous indication continues to be given for degrees of unbalance which would never be encountered in any practical case. Even when both neon tubes are conducting, corresponding to both X′ and Y′ lying in the lower



g. 3.—Chart for estimating the response of the indicator to an unbalanced voltage system ($k = V_S/V_A$).

gment (Fig. 2), as well they might for high system voltages g. $V_A = V_B = 600$ volts, $V_B = -jV_A$) (Fig. 3) and the ethod apparently fails, it is still possible to determine from eir relative brightness which of V_{OX}, V_{OY} is the larger and nce to deduce the phase order. The useful working range en is broader even than that derived from Fig. 3.

(4) VARIABLE FREQUENCY AND THE EFFECT OF HARMONICS

(4.1) Variable Frequency

When the applied voltage has a frequency which is different om that used initially for adjusting the phase-selective circuit own in Fig. 1(*a*), the required relation $R = -a^2Z$ in the phase case, for example, will not be satisfied, and the voltages $_{OX}$, V_{OY} will each depend on both the positive- and the negative-quence components instead of on one or the other of them. ssuming not only that the frequency is incorrect but also that e system applied is unbalanced, and denoting the positive-quence components by V_{a1}, V_{b1}, V_{c1} and the negative-sequence mponents by V_{a2}, V_{b2}, V_{c2}, it can be shown that

$$\left.\begin{aligned} V_A + \frac{2V_B}{1 - j\frac{\sqrt{3}}{\alpha}} &= V_{OX}\left(1 + \frac{2}{1 - j\frac{\sqrt{3}}{\alpha}}\right) \\ V_B + \frac{2V_A}{1 - j\frac{\sqrt{3}}{\alpha}} &= V_{OY}\left(1 + \frac{2}{1 - j\frac{\sqrt{3}}{\alpha}}\right) \end{aligned}\right\} \quad . \quad (1)$$

bstituting V_{a1}, V_{a2}, etc., for V_A and V_B,

$$\left.\begin{aligned} V_{a1}(1+\alpha) + V_{a2}(1-\alpha) &= V_{OX}(1 + j\alpha\sqrt{3}) \\ V_{b1}(1-\alpha) + V_{b2}(1+\alpha) &= V_{OY}(1 + j\alpha\sqrt{3}) \end{aligned}\right\} \quad . \quad (2)$$

ere α is the ratio between the frequency of the applied voltage d the initial calibrating frequency, and the output impedance tween O and X, and O and Y is assumed to be high. Providing values of V_{a1}, V_{a2}, etc., are given or can be measured, ns. (2) enable V_{OX} and V_{OY} to be computed in the general case. en the system is balanced, i.e. when $|V_A| = |V_B| = |V_{a1}|$ $|V_{b1}| = |V|$, say, and $V_{a2} = V_{b2} = 0$, they take the simpler m

$$\left.\begin{aligned} \left|\frac{V_{OX}}{V}\right| &= \frac{1+\alpha}{\sqrt{(1+3\alpha^2)}} \\ \left|\frac{V_{OY}}{V}\right| &= \frac{1-\alpha}{\sqrt{(1+3\alpha^2)}} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

These expressions are plotted in Fig. 4. For a variation in frequency of $\pm 20\%$, the change in V_{OX} is less than $\pm 6\%$ and

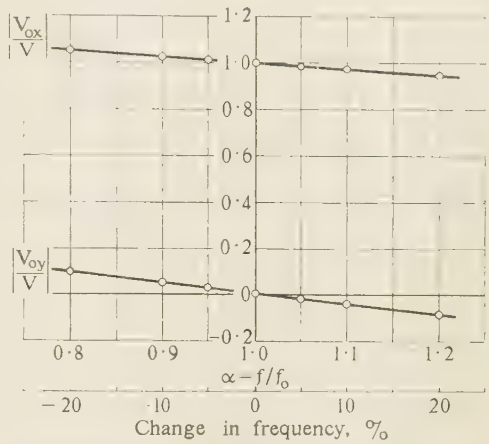


Fig. 4.—Estimated change in bridge output voltages for variations in supply frequency.

the corresponding value of V_{OY}, which should be zero, does not exceed 11% of V_{OX} or of the applied voltage. Thus, for quite wide variations in frequency, one voltage will be considerably in excess of the other, and as a result both lamps will be ionized together only for high system voltages (e.g. greater than about 10 V_S) and even then one of them will be unmistakably brighter than the other.

(4.2) Harmonics

As the third-harmonic voltages in a 3-phase system are equal and co-phasal with one another the effect in the circuit of Fig. 1(*a*) can be readily deduced, and verified experimentally, by considering the same single-phase triple-frequency supply to be connected between O and V_A, and O and V_B. Clearly, by inspection, V_{OX} and V_{OY} will both be equal to the supply voltage, as is also seen by putting $V_A = V_B = V_3$ in eqns. (1), when $V_3 = V_{OX} = V_{OY}$. Thus the triple-frequency voltage appearing across the neon tubes will be the same for both of them and numerically equal to the third-harmonic voltage in the supply. These, and similar voltages of order $3n$, are usually small, and when superimposed on those arising from the fundamental terms will not materially affect the performance of the indicator except under conditions of gross unbalance approaching the limiting case when V_A and V_B are nearly in phase.

Fifth harmonics in a supply system have a relative phase displacement of $\frac{4}{3}\pi$ and together form a 3-phase system but with reversed phase sequence compared with the fundamental components. It follows from eqns. (3), putting $\alpha = 5$, that

$$\left|\frac{V_{OX5}}{V_5}\right| = \frac{2}{\sqrt{19}}, \left|\frac{V_{OY5}}{V_5}\right| = \frac{3}{\sqrt{19}} \quad . \quad . \quad . \quad . \quad (4)$$

Similarly, the seventh-harmonic components together constitute a 3-phase system, but with the same phase sequence as the fundamental. Putting $\alpha = 7$ in eqns. (3),

$$\left|\frac{V_{OX7}}{V_7}\right| = \frac{4}{\sqrt{37}}, \left|\frac{V_{OY7}}{V_7}\right| = \frac{3}{\sqrt{37}} \quad . \quad . \quad . \quad . \quad (5)$$

These arguments can be applied to any harmonic of order $(6n \pm 1)$. As α increases both V_{OX} and V_{OY} tend to the same value, namely $(1/\sqrt{3}) \times$ harmonic voltage.

Those harmonics which produce the greatest change in V_{OX} and V_{OY} are in principle the most significant, and particularly those whose phase sequence is opposed to that of the fundamental components. The effect, which is most pronounced in the case of the fifth harmonic, will be small in practice. Assuming a fifth-harmonic component as large as 20%, $V_{OX5} = 0\cdot04|V_A|$ and $V_{OY5} = 0\cdot14|V_B|$. The corresponding fundamental voltages V_{OX} and V_{OY} are $|V_A|$ and zero respectively and are thus not appreciably modified. Even when there are other harmonics, it is difficult to envisage conditions in practice in which the presence of harmonics alone will produce incorrect indication.

To summarize: whilst it is not easy to assign precise numerical limits to the simultaneous effect of unbalance, variation in frequency and the presence of harmonics in the general case, it is predictable when given the relevant information. Broadly, the voltages applied to both neon tubes are modified to produce, in particular, a voltage across one of them when ideally there should be none. Should this voltage be sufficient to exceed the striking voltage and, further, should the lamps also appear equally bright, it may not be possible to draw any firm conclusions about the phase sequence, but at least the indication will not be misleading. For the "wrong" lamp to be the brighter one, conditions would be such that phase sequence as ordinarily understood would hardly apply.

(5) POLYPHASE SYSTEMS

There are two ways of approaching the wider problem of phase sequence of polyphase systems in general. Thus, any two voltages can be regarded as members of an unbalanced 3-phase system; in principle therefore the 3-phase form of Fig. 1(*a*) can be employed to find their phase sequence and hence that of polyphase systems other than the one for which it was designed; but then, of course, both lamps will have a voltage applied to them. For a balanced bi-phase (90°) supply, for example, DO and DE (Fig. 2) are equal in length but at right angles; OX′ is equal to $2OD \sin 75°$ and OY′ is equal to $2OD \sin 15°$. The voltage across one lamp exceeds the other by a factor 3·5 and, even if the second lamp strikes, for system voltages greater than approximately $3V_S$ there is no doubt about which of them is the brighter. Alternatively, as the method used for the sequence indicator is as general as the symmetrical-component principle on which it is based, it is easily applied to particular polyphase systems by proper choice of component values in the sequence-selective circuits. For a bi-phase (90°) system, for example, the relation $R = -a^2Z$ is replaced by the condition $R = jZ$, and the corresponding circuit consists of a simple assembly of resistors and capacitors [see Figs. 1(*a*) and 1(*b*)] as described in greater detail in the preceding paper. The voltage across V_{OX} is $1/\sqrt{2}$ times the vector difference between V_B retarded by $\frac{1}{2}\pi$ and V_A, and V_{OY} is the difference between V_B advanced by $\frac{1}{2}\pi$, and V_A, divided by $\sqrt{2}$. Figs. 2 and 3 therefore need some modification, but not of a radical kind. In this case, DY′ and DX′ are both equal to DE but are at right angles to it, and the limiting arcs PQ have a radius $\sqrt{2}(V_S/V_A)$OD. When V_A and V_B form a balanced bi-phase system, the voltage across one tube is $\sqrt{2}|V_A|$ and that across the other is zero. All the arguments hitherto advanced for the 3-phase application could be applied to the bi-phase equivalent with appropriate numerical changes. In particular, if V_A and V_B are members of a balanced 3-phase system, the values of OX′ and OY′ are $2OD \sin 75°$ and $2OD \sin 15°$, and a reliable indication will still be given—a result which is comparable with that obtained when a bi-phase system is applied to a 3-phase circuit. Indeed, as shown in the preceding paper, this particular circuit arrangement has formed the basis of an accurate phase-angle meter and can obviously be used as such to determine phase sequence in the general case.

Three-phase supplies are encountered far more frequently tha[n] any other polyphase system, and the slightly more compl[ex] 3-phase bridge circuit may be more acceptable on this accoun[t]. On the other hand, the bi-phase circuit is simpler and mo[re] easily assembled, and will respond if not perhaps equally we[ll] (since there will always be a voltage across the dark lamp), [at] least with sufficient discrimination for most purposes, to 3-pha[se] supplies and, in principle and usually in practice, to other pol[y]phase supplies as well. With only a little extra complicatio[n] one circuit can be employed to the best advantage for bot[h] 3-phase and bi-phase systems as illustrated in Fig. 1(*b*).[4]

(6) CONCLUSIONS

The indicator described is simple to construct and requires onl[y] a few inexpensive components which are easy to assemble an[d] adjust. The circuit is essentially of a fixed-frequency kind bu[t] responds satisfactorily to frequency variations of at least ±20[%] and can be readily adjusted for different ranges if required. [A] similar tolerance on the values of circuit components is pe[r]missible since the effect of maladjustment, implying that th[e] bridge is not being used at the correct frequency, is equivalen[t] to a frequency error. The voltage range is large and can b[e] extended upwards by suitable choice of low-rated limitin[g] resistors in series with the neon tubes, but there is a lower lim[it] determined by the striking voltage of the tubes employed. Powe[r] consumption can be kept to a low level by proper choice of ne[t]work constants.

The indicator requires only two line or phase voltages of [a] polyphase system, and, as it continues to perform satisfactorily fo[r] wide variations in magnitude and relative phase displacement o[f] the applied voltages, it can be used for systems other than th[e] one for which it was primarily designed. Phase-rotation indi[]cators of ordinary construction are not so flexible in applicatio[n].

Simple precautions, such as interchanging lamps, would b[e] taken as a routine measure to avoid a possible but unlikel[y] erroneous indication due to failure of what should be the brighte[r] lamp. By placing capacitors in parallel with the neon tubes, bu[t] not the additional ballast resistors, and simple rectifiers in serie[s] with them, to form primitive time-base circuits in the usual wa[y], the lamp, or lamps, will flash at a frequency determined by th[e] applied voltage. There may be an advantage in the slightl[y] brighter of the two lamps also flickering more rapidly in nea[r] limiting conditions when the lamp voltages are very nearly th[e] same. In other cases, the merits of a flashing indicator are purel[y] objective.

Finally, no attempt has been made to achieve a higher accurac[y] than the problem is thought to demand. Greater precision an[d] sensitivity could be obtained, with a consequent increase in cos[t] and complexity, by using more accurate methods of comparin[g] or even measuring, the bridge output voltages.

(7) ACKNOWLEDGMENTS

The author would like to place on record his continued appre[]ciation of the facilities available in the Electrical Engineerin[g] Department of the University of Bristol where this work wa[s] carried out, and of the advice and criticism of his colleagues.

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(4) Provisional Patent No. 35473, 1954.

DISCUSSION ON
'THE ELECTROLYTIC ANALOGUE IN THE DESIGN OF HIGH-VOLTAGE POWER TRANSFORMERS"*

SOUTH-EAST SCOTLAND SUB-CENTRE, AT EDINBURGH, 3RD DECEMBER, 1952

Mr. R. W. Flux: The main application of the analogue is, of ourse, in the determination of the stress fields due to steady-ate voltages; however, most service and test-bed breakdowns re due to surge conditions, and these are not necessarily most evere at the instant of the initial distribution which, at present, the only impulse condition that can be investigated by the nalogue. It is to be hoped that it will eventually be possible determine the stress fields that exist at any particular instant uring the oscillatory period following the application of an npulse to the transformer.

One unfortunate feature of impulse testing is that a small defect a relatively minor piece of insulation can reduce the impulse rength of a transformer by a half. It is difficult to decide how uch advantage can be taken of the possibility of reducing sulation because of better knowledge of the stress conditions erein. Has the author achieved significant economies in the se of insulation as a result of the information obtained from the nalogue?

Does the author consider that an electronically controlled rvo-motor drive to enable the probe to trace out automatically ny given equipotential is a useful additional feature, or is the tra complication more trouble than it is worth?

Prof. M. G. Say: The physical implications of stress reversal ong the surface of the porcelain bushing shown in Fig. 27(*a*) e said to be obscure. If the surface is a perfect insulator and the resses are not great enough to produce sparkover, the porcelain ill support any variations of stress, including reversal. On the her hand, if the surface is conducting, a conduction current ill flow from the line end to the earth electrode as determined the overall voltage. As a result, the equipotentials will nange in shape, and curve into the porcelain surface so as to iminate reversal. Is there more to the problem than this?

Mr. D. H. Smith: The use of the analogue is confined to points here the field has circular symmetry. This would appear to mit the application of this device, for in very many places in e arrangement of leads and general build-up of a complicated gh-voltage transformer the field conditions are anything but dially symmetrical. It is thus possible to explore only isolated oints of a relatively simple nature, and care must be taken in lating these measurements to the remainder of the structure.

In Section 7.3 it is misleading to say that with care complex elds may be solved with a high degree of accuracy; while it ay well be possible to plot a particular field accurately, the ectrolytic analogue itself can rarely accurately represent the ue conditions in the transformer. One source of error is in e variation of the depth of the bath to represent different rmittivities. The permittivity of insulating materials varies nsiderably with temperature, and tests made at 15°C will not curately represent the conditions obtaining in the same trans-rmer under normal working conditions of 80 or 90°C. In der to obtain accurate results, a number of different models e required comprehensively to plot the field in any one position a transformer. This fact, when considered in the light of the multitude of different field conditions occurring at various points in a transformer arrangement, would seem to indicate that a considerable amount of work is entailed in checking over only one design for a particular transformer.

Will the author say how closely the results of electrolytic-analogue exploration have agreed with actual breakdown tests on full-scale models?

Mr. R. T. Rushall (*communicated*): An indication of the possible permittivity variations is provided by the tolerance of density for pressboard given in B.S. 231: 1950. For the type-II material, as used in transformers, the permitted range of density is $0\cdot9$–$1\cdot15\,\mathrm{g/cm^3}$. From density/permittivity relationships this is equivalent to a variation in permittivity of the oil-treated material of from $3\cdot9$ to $4\cdot5$, or $\pm 8\%$ of the mean value. Similar changes occur in paper, but a further variable is introduced in the wrapped material by inconsistencies in the tightness of wrapping.

A further point, which applies to paper and pressboard in fields other than normal to their surfaces, is the directional variation in permittivity which arises from the orientation of the fibres. Thus when measured along the sheet the permittivity may be 10% or so greater than when measured normally. Here again the effect of a laminated structure, as in wrapped paper, would be to increase the variation, particularly in the case of thin high-density papers.

Will the author comment on the practical significance of these inconsistencies in permittivity and on whether the electrolytic analogue described could be arranged to take into account any directional variation in permittivity of a component material?

Mr. E. G. Williams (*Australia: communicated*): Some time ago I carried out electrolytic-field analysis in connection with the design of a 275-kV air-blast circuit-breaker. A complex wedge-type model similar to that described in Section 4 was made, but by a wood-milling technique instead of the cast-wax method. The former technique was based on the milling of a solid block to a template, usually a print of the general layout of the piece of equipment concerned. After some preliminary work the joinery foreman became so familiar with the technique that it was necessary only to colour the various sections of the print in accordance with a key to the angle required, mark the axis of symmetry, and leave the rest to him. This greatly reduced the engineering, drafting and model construction time involved. Since curved channel sides could not be produced, curved pins and a certain amount of undercutting of the channel sides had to be used to reduce errors at these permittivity-transition surfaces. Such simple techniques have a place in practical insulation design work, particularly where the configuration is not so complex as that of a detailed section of a transformer winding.

A problem encountered during work on outdoor equipment was the representation of resistance glazing or the effect of pollution on porcelain insulation surfaces. To maintain the analogy it seems that small capacitances connected between the "transition" pins and calibrated relative to the electrolyte resistance would be necessary.

* McDonald, D.: Paper No. 1363 S, November, 1952 (see 100, Part II, p. 145).

MERSEY AND NORTH WALES CENTRE, AT CHESTER, 8TH DECEMBER, 1952

Mr. David Morris: To what extent is this apparatus used to plot magnetic fields in transformers, for the determination of leakage reactances and short-circuit stresses? The evolution of empirical formulae for leakage reactance is facilitated by the fact that calculations can be checked by test after construction, but an experimental check for short-circuit stresses is not possible. The applications to magnetic fields are in some respects simpler, because the investigation can be based upon only two values of permeability (unity and infinity), whereas in the electrostatic case a range of discrete values of permittivity must be represented.

In magnetic investigations, magnetic potential can be represented by electric potential and magnetic flux by electric current. Alternatively, a dual representation can be used, conductors being interchanged with insulators and voltages with currents. Are there any corresponding applications of the dual representation in the investigation of electrostatic problems?

Mr. C. V. Jones: In Section 7.3 it is stated that the technique may be applied to the solution of Poisson's equation. Would the author explain how this is accomplished?

Are plots carried out with a level tank of any value in estimating the cylindrically symmetrical field (i.e. the tilted-tank plot)? More specifically, would the tilted-tank plot of the system (shown in Fig. 18) be notably different from the actual diagram? I as because the electrostatic gradients for Rogowski uniform-fiel electrodes are always calculated on the basis of parallel-plar symmetry, whereas the electrodes are actually surfaces c revolution.

My interest in the tank is as a visual aid to teaching the magnet fields of machines, so that I am concerned more with simplicit than accuracy. Tests I have made with Teledeltos paper sugge that the technique will be excellent for the above purposes. Th method consists in using an electrolytic tank with a solid ele trolyte—a sheet of conducting paper. By using a solid tan "voltameter" effects are eliminated and it follows that direct cu rent may be used. The oscillators are replaced by a simple gri bias battery and the detector is any suitable d.c. galvanomete Electrodes are painted on to the paper with a silver suspensio The method of plotting consists in mounting the conducting pape on a sheet of drawing paper on the drawing board with a shee of carbon paper as a separator. With a pointed probe it is simple matter to find balance points without marking the drawin paper, while a heavier pressure at the balance points makes th necessary mark on the paper below. The whole equipment i very simple and inexpensive and rapid to use. Our first result are most encouraging.

NORTH-WESTERN CENTRE AT MANCHESTER, 24TH MARCH, 1953

Prof. E. Bradshaw: To the chemist, the measurement of electrolyte conductance has focused attention on the electrode-electrolyte surface impedance. It is remarkable that Kohlsrauch, over 60 years ago, recommended platinization of electrodes, a frequency of about 1 kc/s, large electrodes and high cell resistance. It would appear that platinization still offers one of the best electrode treatments and one wonders, in view of the small thickness needed, whether such a deposit on brass electrodes would not offer an attractive alternative to the author's steel electrodes. To minimize the effect of surface impedance, it would seem desirable to use water of low conductivity. Has the author considered the passage of water through ion-exchange resins as a means of accomplishing this?

The above comments are prompted by some recent work in this field in which we have been troubled by the variation with time of the impedance between electrodes, which appears to be due to electrode-surface phenomena. It is possible that the conditions imposed by field plotting are not so stringent as those required by overall conductance measurements for the determination of, say, capacitance by conductance analogue, but the reduction of errors due to polarization impedance would seem important for work of the highest accuracy.

Mr. L. H. A. Carr: One of the most important steps in the education of an electrical engineer is the correlation of academic knowledge with the physical problems to which it applies, and the paper is a welcome contribution in this field. It is to be regretted, however, that the author has made the problem sound more difficult than it really is by taking Maxwell's equation as his starting point, while others have equally erred in using Laplace's equation as a basis.*

Neither of these complications is necessary. The subject is much simpler, and its understanding should be well within the capacity of the average Ordinary National Certificate student, as the following argument will show.

If in any space (or in any plane if a 2-dimensional problem is under consideration) there is a property or characteristic which has the nature of a potential or driving force P, and if equ potential lines are drawn for P and for $P + dP$, it is readil seen that the maximum value of dP/dl, termed by conventio "potential gradient," lies in the direction where dl is a minimum i.e. along a line which is at right-angles to both equipotentia lines as dP becomes infinitely small.

If, in a homogeneous medium, there is any property which i proportional to potential gradient, this property, which wi partake of the nature of a movement or flow, acts along lines a right angles to the equipotentials, and the characteristic equatio is obtained:

$$\text{Flow density} = \text{Constant} \times \text{Potential gradient}$$

of which the author's eqn. (5) is an example. This is the onl mathematics required. Eqn. (5) gives the whole story and is th only basis required for what follows.

The importance of the above theorem is that any physica phenomenon that obeys the above law can be simulated by an other physical phenomenon which also obeys it. Of the fou such phenomena frequently met with, namely the electric con duction field, the electric field, the magnetic field and the flo of heat in a homogeneous medium, only the electric conductio field lends itself readily to experimental methods, since alon among the four types of phenomena, air and many convenien solid materials are insulators to the flow concerned; and it i for this reason that analogues in the form of electric conductio circuits are selected for experimental use.

It is true that the fields considered have other mathematica properties. Laplace's equation is one, but this is the result c the law of orthogonality described above, and not the reaso for it.

Mr. E. G. Wright: For a given analogue technique the magn tude of the polarization error and the shape of the error-distribu tion curve depend upon the electrode size and surface finish an the field distribution, but, even at 50 c/s with tap water, the erro can be kept down to a fraction of 1% of the applied voltage fo suitable clean electrodes; for oxidized or dirty electrodes it ma be several per cent. Typical polarization-error curves are show

* HARTILL, E. R.: "The Electrolytic Tank and its Applications to Engineering Design" (*Metropolitan-Vickers Gazette*, 1952).

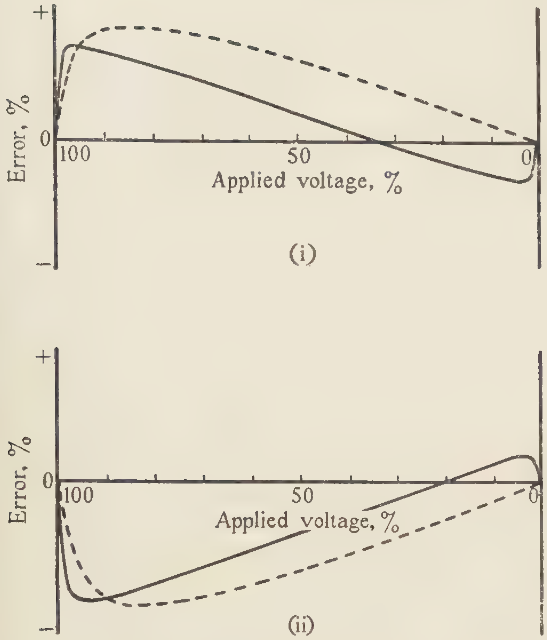

Fig. F.—Typical error-distribution curves for non-uniform fields.

——— Moderately non-uniform.
- - - - - - - Very non-uniform.
(i) Polarization error.
(ii) Meniscus error.

Fig. F(i). For a uniform field the curve would be symmetrical oout the abscissa.

For small electrolyte depths a more serious error can be troduced by meniscus effects at the model electrodes, and the ror distribution through the field is shown in Fig. F(ii). For ectrolyte depths of 0·1 or 0·2in the error may reach a few r cent, but is only a fraction of 1% for depths of about 0·5in.

It may be noted from the curves that the error is not confined the region near the 100% electrode, but may extend over a rge portion of the field. Fortunately both errors act in opposite rections, and although in general they are not equal, they nd to cancel out, so that their combined error may be small.

Mr. R. B. Burtt: A high-speed field mapper using electronic inciples is in course of development at the College of echnology which will give a complete equipotential map of a mple field, as a television-type picture, in 0·04sec. Owing to the high repetition speed of the mapping process, the field map can be observed while the analogue boundaries are moved and adjusted to give optimum field characteristics. Although it is doubtful that such a machine would give any advantage in the mapping of complex fields, much of the preliminary and qualitative work might well be done in this way.

Some examples that occur to me are:

(*a*) The adjustment of the position in the analogue model of a high-voltage conductor with respect to the transformer tank, cores, etc., to obtain a rough idea of the field shape and to determine the best position of the conductor with regard to voltage gradients, etc., before work on the complex model is started.

(*b*) The adjustment of field boundaries so as to achieve zero tangential stress through a wound-paper bushing.

(*c*) By applying a 3-phase alternating potential at, say, 1c/s to a suitable model, a rapid qualitative idea could be obtained of the field configuration during a complete cycle and note made of the phase angle at which particularly high stresses occur.

Mr. E. R. Hartill: Following the method of treatment adopted by the author, we may consider a straight round wire carrying a current of I amperes. The intensity of magnetic field, H, at any radius r is $I/2\pi r$. The flux $\delta\Phi$ per unit axial length of wire contained between two radii spaced δr apart is $(I/2\pi r)\mu\delta r$.

The analogue of this is a round wire probe dipping into a bath containing a uniform unit depth of electrolyte, and into which a current I' (proportional to I in magnitude and direction) is introduced to give a current density ι at radius r of $I'/2\pi r$. It is interesting to note the direct analogy between H and ι using the rationalized M.K.S. system.

The circular flux lines in the problem are plotted as equipotentials in the analogue, the voltage δV between equipotentials spaced δr apart being $(I'/2\pi r)\rho\delta r$ and analogous to $\delta\Phi$. In addition, electrolyte resistivity ρ is analogous to permeability μ.

Fig. G shows a typical field plot between two C-shaped magnets excited respectively by go and return cables in the shaded winding space. These cables were represented in the model by probes dipping into the uniform depth of electrolyte, while the magnets, which were of high permeability, were represented to scale by solid pieces of Bakelite. The current from the probes in one "magnet" flows through the narrow channel formed by the gap, out into the "open sea" between the "magnets," and then back again to the probes in the second "magnet." The equipotentials shown representing the flux lines are all plotted at right angles to these current-flow lines.

In the actual problem, which was the magnet system of a synchrotron, there were a number of such magnets arranged in a circle. A closer approximation than the above 2-dimensional

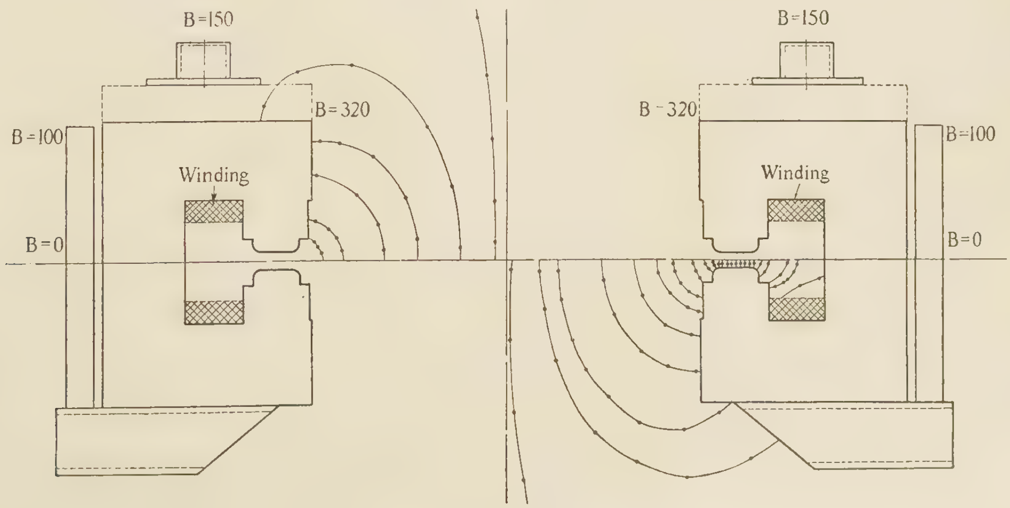

Fig. G.

analogue could have been obtained by making a more complicated model with varying depths of electrolyte to represent rotational symmetry.

In another 2-dimensional model of part of the core and windings of a larger power transformer, the core and yoke boundaries were represented by Bakelite strips. Resistors controlled the currents to the probes representing individual conductor groups. Increased accuracy could have been obtained by representing each conductor, but the model would then have become very complicated.

In neither of the above problems was it possible to plot the internal flux in the copper spaces, since this region was occupied by the probes. This may be unimportant in the first example but may cause errors in the second, where the copper spaces and internal fluxes form a large proportion of the field unde examination. However, by reducing the probes in size by a definite amount relative to the conductors they represent, additional flux lines could be plotted in the resultant increased electrolyte space to such a value that it represented the magnitude but not strictly the distribution, of the internal flux in th conductor.

For a single round wire of radius r, having a uniform curren density, a simple calculation shows that a probe of radius $0 \cdot 61$ would enable the internal flux to be plotted in the analogue without disturbing the external flux distribution. Other ratios can b deduced for rectangular copper spaces, or when flux linkages fo reactance calculations are required.

Mr. H. Diggle also contributed to the discussion at Manchester.

SOUTH MIDLAND SUPPLY AND UTILIZATION GROUP, AT BIRMINGHAM, 5TH APRIL, 1954

Dr. W. G. Thompson: A surprising feature of the electrolytic analogue and other methods for determining stresses in high-voltage equipment has been the time taken for the electrical industry to make use of them.

I had some experience of the electrolytic tank in 1932; although the equipment was comparatively primitive, using headphones and a high-frequency supply to determine when the probe was tracing an equipotential, the results appeared to be quite satisfactory. The type of problem we were interested in was the difference between practical and mathematical values of stress and the trajectories of the lines of force around sharp edges, ranging from the 180° case on the edge of a flat plate to different angles, including the right-angle case corresponding to the corner of a solid conductor, finally to the flat surface of a plate. So far as we could ascertain there was good agreement between calculated and observed results.

About that time 220kV transformers were in use on the Continent; so far as I know, the method employed by the author was not used in their design, but they were still able to make quite satisfactory transformers, many of which are in operation to-day. It is therefore all the more puzzling why the electrical industry has been so slow to adopt this knowledge and to bring it to the present state of perfection which the author has shown to be possible.

I would issue a word of warning, however, on the subject of working and thinking in analogues; and whatever success we may achieve with methods similar to those described by the author, it is still very desirable to correlate the results with those obtained with an actual transformer. In the latter respect there are various possibilities of directly measuring the field strength and direction of the lines of force by such means as dielectric needles and valve voltmeters. The latter are especially applicable to insulated equipment in showing up effects produced by corona discharges, which are, of course, absent from the electrolytic-tank analogue.

The author introduces his paper in terms of vector analysis and Maxwell's equations, but I suggest that the vital part of the whole story, so far as stress raising is concerned, would be given by the equation $\mathscr{E} = \text{grad}\ \Phi$. This has a particularly important bearing on my previous remarks about the examination of the effect of angles of conductors and how the right angle with a sharp corner produces a raised stress.

It would also be interesting to know to what extent transformer troubles have been directly identified with electric stress. If we set out to design a transformer in conformity with the methods the author has suggested and then use the ordinary manufacturing techniques available, would we be completely free from transformer faults, or are there other factors which enter into the construction in practice to which the electrolytic analogue does not appear to pay sufficient attention? One could imagin such things as the variation of quality in insulation or th manner in which it is applied. None of these factors would b revealed in the analogue study of the transformer design in a electrolytic tank. I do not say this in any way to decry th author's methods, because we employ them in a similar manner but I do feel that when working in terms of analogues it i doubly important to keep practical details in mind, because it i so easy to get into a mental condition where one accepts th shadow of the analogy and neglects the truth of actual practice

Miss M. K. Weston: The electrolytic tank which I have bee using differs in some respects from the author's and may therefor be of interest. A transparent plotting table is mounted directl above the tank, and a probe assembly suggested by Professo Bradshaw is now used. In this arrangement four magnets ar fixed to each of two plates which run on ball bearings on bot sides of the table, one on top and the other on the lower face The attraction between the magnets is sufficient to keep th plates together, so that on moving the top plate the botton plate follows perfectly. A probe with illuminated cross-wire directly above it is attached to the bottom plate, so that th shadow of the cross-wires on tracing linen fixed to the plottin table marks its position. This arrangement is convenient because the probe may be moved in any direction. This not onl saves time, but, by moving the probe at right angles to th equipotential line being plotted, and hence along the greates voltage gradient, enables the greatest sensitivity to be obtained The tank is similar to the author's in that it can be tilted; w also use tap water as the electrolyte, and a frequency of 1 kc/s.

Model making requires far more time than plotting, and ever possible advantage of any symmetry in equipment should b taken to simplify the models without detracting from the accurac of simulation. We have found it convenient to fabricate model from synthetic-resin-bonded-paper board. To simulate a spou insulator on metalclad switchgear with a bushing inserted, shape pieces of board of the requisite thickness are fixed to a base board with a synthetic-resin adhesive; gaps are left between th pieces of differing thickness and are afterwards filled with wa so that the pins may be inserted. Wax is also used in region where minor changes are to be made. We have found bras coated with colloidal graphite to be convenient for electrodes.

Mr. J. R. Reed: I agree with the author that the electrolyti analogue is an extremely useful tool in the study of impulse voltage distribution, but it must be borne in mind that it can giv only a good approximation to the truth. To mention only on factor: the assumption of a unit function is an approximation and in our experience it is not always necessary to simulat every conductor in the winding. Thus, in a plot taken to analys the field in the vicinity of the static ring the adjacent conductor

e individually represented while those more remote, in both the v. and l.v. windings, are lumped. The distribution found in at region agreed with that obtained by tests on the transformer ith the recurrent-surge oscillograph and so justified the use of ich simplified models.

The second point is in connection with the siting of bushings. he potential varies up the windings and along the bushing, and is desired to fit the bushing into the field of the transformer ithout causing stress concentrations. One method, as used by e author, is to take a number of plots at various cross-sections. nother is to use a 3-dimensional model, replacing the windings y sectors of cylinders fixed at the relevant potentials, and to mulate the bushing by a model with a uniform potential radient along its surface. Then, because the line joining the xes of winding and the bushing is a plane of symmetry, this can e made the water surface. The only precaution necessary is at the depth of water should be large compared with the radius f the bushing. In most cases the radius of the windings is ufficiently large for it to be permissible to replace the cylinders y sheets, and the model then becomes very simple. It is, of ourse, impossible to simulate changes of permittivity, but we nsider it easier in many cases to modify the plots to account r this than to attempt to construct the picture from a number f 2-dimensional plots.

Mr. N. P. Koh: It seems that all these tests are set up to simulate capacitance effects, and therefore the planes of equipotential are easily visualized. How much more complicated would it be to study the magnetostatics of a transformer, especially from the aspect of zero sequence impedance?

Dr. E. Friedlander: Although it is model-making which is the time-consuming factor, most engineers will like to reduce the time needed for plotting, and I wonder whether the sweep-balance-recorder technique has been used for this purpose. This technique was developed by Keinath* in America for plotting automatically quick variation of stresses, temperatures or other variables to be recorded from bridge measurements. I think this technique contains an idea which may also be useful for plotting the results of an electrolytic analogue. When the probe electrode crosses the equipotential chosen by the potentiometer adjustment, the phase angle between the applied voltage and the bridge current swings through about 180°. This can be used for producing a short voltage impulse, making a dot on, say, Teledeltos paper whenever the probe electrode scanning the whole plane crosses the chosen equipotential. In this way the curve can quickly be plotted, with the probe electrode moved either automatically or by hand.

[The author's reply to the above discussions will be published later.]

* KEINATH, S.: "Multiple *X–Y* Recorder for Testing Quartz Crystals," *Electronics*, January, 1945.

DISCUSSION ON

"IMPULSE PUNCTURE CHARACTERISTICS OF MASS-IMPREGNATED PAPER-NSULATED CABLES, WITH SPECIAL REFERENCE TO TESTING PROCEDURES"*

Dr. B. Salvage (*communicated*): The author has succeeded in pro-ding a considerable volume of experimental information which ll be of value to both cable maker and user, particularly in the rmulation of impulse tests. I should like to make two comments.

First, in each of the three cables tested, grading of the electric by paper-tape thickness was employed. This may have incided with grading by paper density, and hence permittivity, t no mention is made of this in the text. If so, the effect ould be considered in the calculation of the maximum impulse ncture stresses, the stress distribution under impulse voltages ing determined by the capacitance of the dielectric. Permit-ity grading, if present, may also possibly have a bearing on e observed variation of the maximum impulse puncture stress th the conductor size.

Secondly, the measurements show that the impulse puncture ltage is independent of the duration of the wavefront for vefronts of from 1 to 11 microsec. This is an important conclu-n, which, as the author suggests, should lead to a considerable crease in the permissible wavefront duration when testing high-ltage cables. It is very common, however, to test cables gether with their associated joints and sealing ends, in which the ctric stress is not purely radial but has a longitudinal com-nent, and it is, of course, well known that the breakdown aracteristics of oil-impregnated paper dielectrics are very ferent when the stress is in line with the paper surfaces from se when the stress is normal to the paper. Any information author may have on the effect of the duration of the wave-nt on the longitudinal impulse breakdown strength of impreg-ed paper would be very interesting and helpful. In the ence of such information it may be unwise to use extended wavefronts up to 10 microsec for testing accessories in addition to cables.

Mr. P. R. Howard (*in reply*): The effect of conductor size on the breakdown stress is being studied on model samples, where similar paper tapes are used and the insulation thickness is the same; with the limited number of results so far obtained there is an indication of reduction of strength with increase of conductor size. This trend can also be inferred from the results given by Davis,† and Dr. Salvage‡ in his recent paper gives results on 66-kV cable samples showing a decrease in strength with increase of conductor size, but he dismisses this effect as not significant. Since the values of breakdown stress obtained with the three types of cable used agree with the figure of 1 000 kV/cm generally accepted for mass-impregnated paper cables, it is unlikely that there was any permittivity grading accompanying the grading by paper thickness.

It is emphasized that the data offered is related purely to cables and it is not suggested that it is applicable to joints and sealing-ends, where the field has a longitudinal component. The acquisition of such data would call for considerable experimental effort in the preparation of suitable samples. Nevertheless, work is contemplated on model samples with field arrangements obtaining in joints and sealing-ends to determine whether the data on cables have wider application. Experience of present-day designs indicates that joints and sealing-ends are made considerably stronger than the cable, so that it is unlikely that trouble would be experienced with long wavefronts on experimental arrangements involving joints and sealing-ends.

* HOWARD, P. R.: Paper No. 1515 S, June, 1953 (see **100**, Part II, p. 315)

† DAVIS, R.: "Impulse Electric Strength of High-Voltage Cables," *Journal I.E.E.*, 1942, **89**, Part II, p. 52.

‡ SALVAGE, B.: "The Impulse Breakdown of High-Voltage Cables of the Solid and Gas-Cushion Types," *Proceedings I.E.E.*, Paper No. 1468 M, March, 1953 (**100**, Part IIA, p. 163).

DISCUSSION ON

"THE FIRST STAGE OF THE ELECTRIFICATION OF THE ESTRADA DE FERRO SANTOS A JUNDIAI"*

BEFORE THE EAST MIDLAND CENTRE, AT DERBY, 14TH APRIL, 1953, AND THE NORTH-EASTER CENTRE, AT NEWCASTLE UPON TYNE, 8TH FEBRUARY, 1954

Mr. R. S. Pedder (*at Derby*): Fig. 8 shows that the steel structures which support the overhead-line equipment carry the earth wire, the 33-kV 3-phase transmission lines, duplicate 2·2-kV signal supply circuits and catenary suspension for supervisory control. This is rather an unusual arrangement compared with practice in this country, and it seems that all the eggs have been put into one basket.

I do not know what the atmospheric conditions are in Brazil, but I suggest that there might be a risk of lightning, and I should be interested to know what special arrangements are made here for maintenance of these steel structures and for work on individual circuits. Are maintenance staff allowed to work on any of the circuits while other circuits are alive, what precautions are taken, and would it not be better to install 33-kV transmission lines independently of the overhead structure? I imagine that a fair amount of maintenance is required on these steel structures—have they been treated in any special way? Could the authors say whether it would be possible to lay cables, or has this point been ruled out on account of cost?

In Section 4.12 it is mentioned that comprehensive instruction books were issued describing the various items of apparatus, drawing particular attention to the main parts requiring attention. I should like to know if there is anything special about the equipment of this substation (rectifiers, etc.) for it seems to me that unusual maintenance is required.

With respect to supervisory circuits, mentioned in Section 4.11, perhaps the authors could say what kind of faults have occurred on this cable. Were they due to vibration or blast, and was the cable penetrated anywhere?

In Section 8.3 it is stated that the positive feeders from the substations and cabins are bare strands and the negative feeders are cables. It would appear that the arrangement is a very complicated one, and I should be glad if the authors would say whether there was any great saving in cost. There is again the question of bare cables on the structure which makes it more difficult for the maintenance men.

Mr. W. E. Marrian (*at Derby*): I note that steel-alloy girder-type starting resistors are used in the initial stages of the resistance bank, but I should have thought that it would have been preferable to have had either all cast-iron or all steel-alloy.

I see that h.v. cable is run in ducts whereas the control cable is run in conduit: I should have thought that it would have been simpler for all the cables to be run in ducting.

I should like to know whether arcing has occurred in the Timken roller-bearing axle-boxes, since I notice that a standard carbon brush is used on the axle to by-pass the current. We get a certain amount of trouble on British Railways.

I was interested to see that flange lubricators are fitted to the locomotive, and I should like to know whether any lubricators have been fitted on the track itself or whether the tyres are made of steel of higher tensile strength than usual to account for the high mileages.

No mention has been made as to whether one or two pant graphs are used. I should like to know whether two pantograp have been used, and if so, what effect it has on the life of th contact strips. I do not know whether these strips are of copp or some other material.

In Section 7.1 it is stated that lightweight construction on th principle of the hollow-beam structure is used. I query the ter "lightweight" since the motor vehicle on the Liverpool–Southpo line weighs 42 tons against 50 tons in the motor units under di cussion, which in turn compares with 55–56 tons on some of o older British Railways stock. Referring again to the Liverpoo Southport line, I think we had roughly 30 tons for the structu and 12 tons for the electrical equipment.

I am interested to note, in Section 7.7, that the driver contro the doors. This is not British Railways' practice, and I shou like to know whether the closing of the doors is interlocked any way with the control equipment for the driving motors, ar whether there is any particular reason why the driver shou control the doors. Also, as it is stated that there is an assista driver in the locomotive, have the people in Brazil considere using only one man?

Mr. R. C. Woods (*at Derby*): Was the non-electrification the highland portion of the railway due to difficulties of suppl

Mr. H. E. Knight (*at Derby*): Are we not getting back to th age-old question of the necessity for wasteful non-regenerati braking and its intricate absorption equipment?

Has the question of going back to rotating conversion equi ment as opposed to rectifiers ever arisen? On looking throu the complex equipment and complicated operation, it mak one wonder whether rectifiers are in fact to hold their own.

Brazil is in the earthquake area—what has been the reacti of this on the concrete structures in that part of the world?

Was the possibility of using direct high-voltage a.c. fe with conversion equipment on the locomotive itself consider for this particular project? Lastly, what extra precautions a necessary in South America to exclude tropical vermin from th electrical equipment?

Mr. G. P. Cundall (*at Newcastle upon Tyne*): Capital equi ment is usually modified in order to make it more reliable a safer; or to make it more profitable, either by improving its pe formance and earning capacity or by reducing its maintenan and running costs. Generally, electrification will be justifia only by financial considerations.

It must be difficult with changing relative costs of materi and fuels (particularly when the cost of fuel oil—for Diesel Diesel-electric locomotives—can be changed so drastically tax changes) to decide when electrification is going to economical in the long run.

Obvious economies in transmission and the number of su stations needed can be achieved by the use of h.v. alternati current at power frequency. Because of the extra heig required for the insulation, however, such a supply is best suit to new routes, or to routes where there are not many existi low bridges and tunnels. Brazil is a developing country, and

* CHATTERTON, R. J. B., and ROONEY, D. H.: Paper No. 1456, January, 1953 (see **100**, Part I, p. 319).

oubt new railway lines will be laid, and because of this it seems at alternating current deserved consideration in the present ise. It would be unfortunate surely under such circumstances be influenced too much in choice of voltage by the need for andardization with a previous scheme. It would be interesting know whether alternating current was considered. There ems to be little uniformity of opinion on this subject, direct urrent being in general favour here and in France, Italy and olland, while alternating current is favoured in Germany, witzerland and Sweden. In the United States both systems are sed.

The supporting structure shown in Fig. 8 is simple. Was the se of welded tubular steel considered for larger spans? What e the authors' opinions on its possible use? Structures can sually be painted only at night when the power can be switched ff: maintenance charges are therefore higher than for similar quipment which is not associated with electricity. Are there y cases where the use of pre-stressed concrete or aluminium loy has proved economical because of the lower maintenance osts?

Copper is very expensive nowadays: I remember reading of Continental firm manufacturing a solid steel-aluminium contact ire. Because of the relative cheapness of steel and aluminium, randed conductors of steel-cored aluminium are economical or transmission. Their manufacturing costs will be closely omparable with those for stranded-copper conductors but the anufacturing costs of steel-aluminium contact wire will not ompare so closely with those for cadmium-copper wires. It ould be interesting to know how such wire compares in cost nd durability with copper-alloy wire.

Mr. P. Bingley (*communicated*): My remarks all apply to the ectifier equipments.

The authors have confirmed that the a.c. system was non-eceptive to the normal 17th- and 19th-harmonic currents, and am most interested to know what exactly is implied in this case. an it be concluded that the equivalent circuit for the supply ystem is represented by two parallel rejector circuits in series, ach tuned to one of the harmonic frequencies mentioned?

Having studied Mr. Cock's contribution to the discussion, attempted to make a comparison of the relative sizes of trans-ormers and filter equipments for the 6-phase system described nd a 12-phase system of equal capacity, both arranged to give ne telephone-harmonic-factor performance quoted.

I was unable to do this because the performance figures and ata given in the paper do not appear to relate to one another, nd I shall be glad if the authors could indicate where the iscrepancy lies.

Secondary voltage is given as 2 460 volts (presumably on ormal tap), thus for the fork-connected secondaries shown, the eoretical direct voltage at no-load would be 1·35 times greater, e. 3 320 volts, and the actual no-load voltage should differ from is only by arc-drop volts. The figure of 120 volts obtained us seems rather excessive—can the authors confirm this value, nd also that for the arc-drop at full load with the modified anode onstruction?

Moreover, the direct voltage at 100% load would appear to be 967 volts, so that the average output of the transformers, lowing 10 kVA for the star tertiary shown, works out as 256 kVA. Taking the figure of 3 080 kVA given, one might xpect the transformer copper losses to be about 36 kW at 100% ad. This would leave 16 kW for all other losses and imply an c-drop considerably better than 23 volts.

It would be enlightening if the authors could say how much the regulation between no-load and full load is due to losses, nd how much is due to reactance within the equipment itself. uch data would enable the magnitudes of the important harmonics on the d.c. side to be estimated, and a comparison between 6-phase working and 12-phase working, both with filter equipments fitted, could then be made.

It can be shown that for rectifier equipments having similar regulation and equal capacities, the average output of a delta-fork connected transformer is almost 7% greater than that for a delta-quadruple zig-zag counterpart. The 20% excess cost of the latter over the former would therefore seem difficult to justify on equipments of this size where the anode circuits usually subdivide into groups of twelve as easily as into groups of six.

Mr. S. A. Vincze (*New Zealand: communicated*): Analysis of the figures given in the paper reveal, *inter alia*, that the linear density of annual energy consumption (l.d.e.) of the electrically operated Mooca–Jundiai section amounted to 27·5 kMWh/year: 41 route miles = 670 000 kWh/route mile/year in 1951—measured by the supply company's apparatus in the incoming 88-kV transmission lines—indicating that the electrification was well justified.

This was confirmed by the authors in their reply to the discussion when giving the operating costs of steam, Diesel-electric and straightforward electric traction respectively.

Had all traffic on this section been hauled electrically, the l.d.e. would have amounted to 1 500 000 kWh/route mile/year.

As a comparison, the l.d.e. figures for various sections of British Railways are compiled in Table B, and those of some foreign railways in Tables C and D.

In view of the interrunning with 620 route-mile Brazilian railways already electrified by that system, the choice of 3 000 volts d.c. for the Santos–Jundiai section appears more or less justified, though the limitations of the system are well brought out in the paper. Among these are:

(*a*) The close (approximately 13·7 mile) average substation spacing and the correspondingly low load-factor of the substation equipment.

(*b*) The substantial copper section ($0 \cdot 62\,in^2$/track) and its heavy supporting structures (approximately 3 000 tons/118 track miles or 25·4 tons/track mile steel used).

(*c*) The difficulty of accommodating a 500-h.p. 1-hour rating traction motor per axle, notwithstanding the broad 5 ft 3 in gauge, whereas more than 1 000 h.p. per axle can be readily accommodated in single-phase a.c. locomotives even on the standard 4 ft 8½ in track.

Both the copper and the steel used compare unfavourably with the a.c. single-phase systems, which require approximately one-third of the copper and less than 40% of the steel used with the above electrification.

Compared with the Swiss Federal Railways' RE4/4 locomotives, which require their tyres to be turned after only 186 000 miles* even the 500% improved performance of 70 000 miles between tyre turnings with the Santos–Jundiai locomotives seems rather poor. One cannot escape the impression that the large difference in performance is due, among other things, to the heavy unsprung weight of the nose-suspended axle-hung traction motors and to the C_0–C_0 wheel arrangement of the Brazilian locomotives as compared with the totally spring-borne, though more powerful, motors and B_0–B_0 wheel arrangement in the bogies of special design of the Swiss locomotives.

I should like to have the authors' opinion on this and also their opinion on whether dispensing with the flanges on the wheels of one axle (preferably the middle axle) of each bogie altogether would not improve running in curves in general and flange wear in particular with their locomotive.

I should like to know whether the ton-miles referred to in conjunction with steam, Diesel-electric and electric locomotives are trailing train weights or whether they include the weight of

* MEYER, E.: *Railway Gazette*, 1949, p. 767.

Table B

British Electrifications*

Section	Approximate route miles	kWh/route mile/year	System
London Transport	169·5†	4 580 000	630 volt, d.c. 4-rail
Manchester–Altrincham	8·7	1 290 000	1 500 volt, d.c. overhead
Southern	709	934 000	660 volt, d.c. 3-rail
Manchester–Bury	14·0	842 000	1 200 volt, d.c. 3-rail
Liverpool–Southport	37·0	796 000	630 volt, d.c. 3-rail
Wirral	10·7	600 000	650 volt, d.c. 3-rail
Tyneside	43	580 000	660 volt, d.c. 3-rail
Lancaster–Heysham–Morecambe..	9·5	63 200	6 600 volt, a.c. 25 c/s‡

* Derived from papers by S. B. Warder, C. M. Cock, and T. S. Pick and R. Dell (see 1950, 97, Part IA, pp. 140, 6 and 27 respectively).
† Total 186·25 route miles but the L.T.E. provides power for only 169·5 route miles. The remaining 16·75 route miles are supplied by other sections of the Railw Executive.
‡ Now 50 c/s.

Table C

Foreign Metropolitan and Suburban Electrifications*

Railway	Approximate route miles	kWh/route mile/year	System	Year
Paris Metropolitan	64	4 000 000	650 volt, d.c. 3-rail	1930
Hamburg Metropolitan	21	2 200 000	1 200 volt, d.c. 3-rail†	1937
Berlin Metropolitan	158	1 950 000	800 volt, d.c. 3-rail	1937
Copenhagen Suburban	24	1 060 000	1 500 volt, d.c. overhead	1937
Brussels–Antwerp..	36	946 000	3 000 volt, d.c. overhead	1937
Vienna Metropolitan	17	710 000	1 500 volt, d.c. overhead	1937

* Vincze, S. A.: "Economics of Long Distance Electrification," *Railway Gazette*,1950, p. 487.
† Converted during the war from 25 c/s 6 kV single phase.

Table D

Long-Distance Main-Line Electrifications

Railway	Approximate route miles	kWh/route mile/year	System	Ref. Year
Natal (SAR and H.)	404	600 000	3 000 volt, direct current OH	1947
Italian State (a.c. sections)	1 240	580 000	3·7 kV, 3-phase $16\frac{2}{3}$ c/s a.c. OH	1937
France (P.O.)	410	530 000	1 500 V d.c. OH	1937
Holland State Ry.	349	464 000	1 500 V d.c. OH	1937
German Reichsbahn	1 459	464 000	15 kV, 1-phase $16\frac{2}{3}$ c/s a.c. OH	1937
Austrian Federal	686	412 000	15 kV, 1-phase $16\frac{2}{3}$ c/s a.c. OH	1950
Italian State (D.C. sections)	1 210	402 000	3 000 V d.c. OH	1937
Swiss Federal Ry.	1 330*	390 000*	15 kV, 1-phase $16\frac{2}{3}$ c/s a.c. OH	1937
New Zealand Rys. (Wellington electr. area)‡	31	355 000	1 500 V d.c. OH	1952
Hungarian State Ry.	117	312 000	15 kV, 1-phase 50 c/s a.c. OH	1937
Sweden State Ry.	2 796	266 000†	16 kV, 1-phase $16\frac{2}{3}$ c/s a.c. OH	1937
Norway State Ry.	409	226 000	16 kV, 1-phase $16\frac{2}{3}$ c/s a.c. OH	1937

* 2 435 route miles in 1947; 1 525 route miles and 464 000 kWh/route mile/year in 1944.
† 323 000 kWh/route mile/year in 1945.
‡ Main line and suburban electrification.

e locomotive; also the average train weights (with and without comotive) hauled by steam, Diesel-electric and electric loco-otives.

Messrs. R. J. B. Chatterton and **D. H. Rooney** (*in reply*): In ply to Mr. Pedder we would state that the installation of the -kV transmission lines mounted as bare-wire circuits on the rtal track-structures, rather than on independent masts or as sulated cables, provides the most economical arrangement for e small copper section required. The material cost of the rangement adopted is less than one-quarter of the cost of an sulated cable.

Up to the present time very little maintenance work has been cessary on the structures. For normal overhead-equipment aintenance all circuits on one track are isolated and earthed fore any work is commenced; the other equipments are ept alive.

We confirm that there is nothing special with regard to the uipment which would require more than the usual amount of aintenance.

As a result of the quarry-blasting operations, the lead sheath the aerial pilot cable was pierced by flying fragments of rock.

Where it is possible to locate substation or track-cabin ildings close to insulated overlaps in the track equipments, e bare-wire circuits adopted are a more economical arrange-ent than insulated cables laid at the surface of the ground in oughing. It is agreed that bare-wire circuits cause certain fficulties in access for maintenance work. Insulated cables positive feeders do, however, necessitate the provision of aling ends and take-off clamps for connections on to the track uipments, whilst the connections for the bare-wire circuits are latively straightforward and easily maintained.

We agree with Mr. Marrian that it would have been pre-rable to use starting resistors all of one type, but it will be opreciated that if cast-iron grids had been used in the first ree high-resistance notches, the total weight of the resistors ould have been considerably increased owing to the number grids required. It was therefore in order to save both weight ad space that steel-alloy resistors were employed, as stated in e paper.

The l.v. control cable was run in conduit to protect it against echanical damage and to segregate it from the h.v. power bles. In general, the outside diameter of h.v. cables necessi-tes large-diameter conduits, with obvious wastage of space and crease in cost. Furthermore, l.v. cables frequently have rtuous runs when they are required for coupling into panels ad connection boxes; this would necessitate their running in nduit in any case.

There is no evidence to date that the Timken roller bearings e pitting owing to the passage of return currents through em.*

The number of rail lubricators used was considerably increased llowing the locomotive flange-wear referred to in the paper. nese lubricators are spaced at intervals of 3–4 miles along the ack. In this respect we should like to make it clear that it as a combination of flange lubricators and harder tyres fitted the locomotives which reduced the flange wear initially. ne increased use of rail lubricators followed afterwards. The res finally fitted to the locomotives had an ultimate tensile rength of between 70 and 75 tons/in^2.

We commented on the reason for fitting two pantographs in ır reply to Mr. Dodridge in the London discussion. Copper ntact-strips are used on the pantographs.

We consider that direct comparison with the Liverpool– outhport stock cannot be taken too far. The E.F.S.J. stock, whilst having approximately the same length and width of superstructure as the Liverpool–Southport stock, was designed for use on a 5 ft 3 in track gauge against the standard gauge of the Liverpool–Southport stock. Furthermore, the equipment on each motor-coach was approximately 6 tons heavier, since it was designed for operation at 3 000 volts against the 580 volts in the case of the Liverpool–Southport stock.

The door equipment is not interlocked in any way with the control equipment. The Railway specified that the driver should operate the door, brake and control gear.

By the "highland" portion of the railways we assume that Mr. Woods is referring to the Serra incline, which involves the ascent of 2 500 ft in 6 miles. The principal reason for not electrifying this portion of the line was the cost involved. Since the gradients are 1 in 10 on the old Serra incline and 1 in 8 on the new Serra incline, adhesion locomotives would be impracticable and rack locomotives would have to be provided.

We would inform Mr. Knight that regenerative braking was used on the E.F.S.J. mainly to save brake-block wear—energy conservation was incidental. In general, regenerated power is absorbed by other locomotives, and it is only when this loading is not available that the resistors in the substations are operative. In view of the above fact, the amount of surplus regenerated power was not considered to be great enough to warrant the use of rotating machines or inverters. With regard to the latter, care has to be exercised owing to the possibility of harmonic currents causing difficulties in the a.c. supply system. In our opinion the control equipment is not complicated, and it is interesting to note that similar schemes are being used in new electrification projects in South Africa and Australia.

We doubt whether there will ever be a return to rotating conversion equipment. When mercury-arc rectifiers are considered, it will be found that they provide many advantages over their rotating counterparts, with reductions in cost, maintenance and no-load losses. Substation floor designs can be simplified, and for remote controlled substations mercury-arc rectifiers do not give rise to the problems of paralleling and synchronizing that are presented by the rotating equipment.

As to the use of concrete structures, we would point out the majority of the buildings in the city of São Paulo are made from reinforced concrete, and, furthermore, these buildings are skyscrapers comparable with some of the highest buildings in North America. Because of this, we have no qualms in using reinforced concrete track-substation buildings and switchgear structures.

The use of h.v. alternating current was not considered. Apart from the fact that inter-running with the Paulista Railway was a requirement, the Brazilian Government decided, in 1934, to adopt as a standard the 3 000-volt d.c. system.

No more than normal precautions were taken to protect the equipment against vermin. This point has been given careful attention at various times, but we have not experienced difficulties of this nature.

In reply to Mr. Cundall, the minimum traffic density at which electrification becomes economical in the United Kingdom is said to be from three to four million trailing ton-miles per annum per mile. A comparative figure for Brazil is difficult to compute, but as explained in the reply to Mr. S. B. Warder, so far as the E.F.S.J. is concerned, economic justification is not the most important reason for electrifying, but rather its strategic value.

For information concerning tubular-steel, aluminium-alloy and pre-stressed-concrete track-equipment structures, we would refer Mr. Cundall to the paper by Messrs. Crompton and Wallace.*

* See also the authors' reply to the London discussion: *Proceedings I.E.E.*, 1953,), Part I, p. 335.

* Crompton, O. J., and Wallace, G. A.: *Proceedings I.E.E.*, Paper No. 1425, November, 1952 (100, Part I, p. 133).

It is not considered that steel-cored-aluminium conductor is a satisfactory alternative to copper strand for use as catenary wires for traction equipment. When compared with a copper catenary of equivalent sectional area and for similar equipment layout conditions, the size and weight of the s.c.a. conductor necessitates a substantial increase in the wire tension, with a resultant increase in the cost of structures and foundations. Such an increase in wire tension is essential if the equipment is not to "blow off" the pantograph under certain windage conditions.

We understand that some Continental systems have installed an aluminium contact-wire with a steel-insert collecting surface, but we believe that such installations were carried out at times when copper was scarce. Apart from the "blow off" considerations, the principal disadvantages of steel-aluminium contact wire for railway electrification work are: (*a*) the corrosion of one or both metals; (*b*) the small sectional area of the steel collecting surface limits its use to relatively lightly-loaded d.c. or high-voltage a.c. systems; and (*c*) there are difficulties in joining together lengths of the steel insert so as to provide a "kink free" contact surface for a normal-tension length of approximately a mile.

The E.F.S.J. is a main-line mixed-traffic system, and it is interesting to note that its linear density of energy consumption compared favourably with similar railway systems referred to in Table C prepared by Mr. Vincze.

Concerning the limitations referred to by Mr. Vincze we would reply as follows:

(*a*) The average substation spacing obviously depends upon the traffic density and the maximum voltage-drop allowed, amongst many other important factors. This should be borne in mind when comparing various railway systems. With regard to the load factor, we consider that the 33·8% load factor of the E.F.S.J. compares favourably with similar railway systems, e.g. the Natal–Glencoe section of the South African Railways (32·5% load factor), and the Chicago, Milwaukee—St. Paul and Pacific Railway (19·8% load factor).

(*b*) We agree with the remark concerning the reduction in copper section for a high-voltage single a.c. system. We do not, however, agree that the adoption of high-voltage a.c. overhead-line equipment would have resulted in a saving of 60% in the total tonnage of steel structures. With high-voltage traction equipment, the track structures would not have been required to carry any 33-kV transmission lines or supervisory control cables, but on the heavily curved E.F.S.J. route it is considered that the saving in structure tonnage would have been only of the order of 20–30%.

(*c*) Mr. Vincze appears to have overlooked the fact that a.c. machines are rated at a higher percentage of their maximum speed than are d.c. machines. As an example, it is common for the speed at the one-hour rating of an a.c. motor to be of the order of 70% of the maximum machine speed, compared with about 50% for d.c. machines operating at 3 000 volts. So far as the traction motors for the E.F.S.J. are concerned, they were designed to meet specific conditions, and there would have been no advantage in using machines of larger output. There is no reason, however, to suppose that d machines of larger output could not be designed if necessary. As matter of interest, 1 200h.p. d.c. traction motors are now in use France.

Referring to the Swiss Federal Railway RE4/4 locomotive we are unable to understand Mr. Vincze's comparison. Apa from the obvious differences in the springing, etc., which m slightly affect the issue, surely the chief point at issue is t large difference in wheel arrangement and bogie wheel-bas The Swiss locomotives have a B_0–B_0 wheel arrangement a bogie wheel-base of approximately 10ft against a C_0–C_0 whe arrangement and a 15ft 9in bogie wheel-base for E.F.S.J. Th factor very considerably influences flange wear. It is notewort that recently-received information indicates that the avera mileage between tyre turnings is now 92 000. Individu locomotives have operated up to 120 000 miles between turning

With regard to dispensing with the flanges on the wheels any one axle, in our opinion, which has been borne out actually observing the tracking of the bogies at speed, th would have served no useful purpose. Furthermore, it is n justified unless the bogie will not negotiate the minimum curv which the E.F.S.J. locomotives do easily. The result of removi the flanges for any one pair of wheels is to increase the flan forces on the remainder. It has been found that rather tha decrease the flange width, better results can be obtained increasing the lateral movement of the axles, particularly t middle one.

The weights of freight trains hauled on the system are general limited to about 600 tons by the space available in the shunti yards. Passenger trains of 700 tons, however, are quite norma The latter have heavy American-built coaches weighing abo 70 tons each which reduce the train lengths considerably.

In reply to Mr. Bingley we confirm that the a.c. system ma be considered in the manner he suggests.

The approximate arc-drop voltage is 20 volts on the basis 3 300 volts and not 3 200 volts being obtained at no load. Th transformer mean output of 3 080 kVA makes an allowance f the effect of overlap, and if this is disregarded the actual val becomes 3 145 kVA. Neither of these figures includes t 15 kVA tertiary rating.

The total copper loss of the transformer and anode reacto and d.c. reactor amounts to 28·5 kW. The total regulation 300 volts between no load and full load is made up as follows:

	Vol
Rectifier transformer reactance	11
Main supply transformer and system reactance	10
Rectifier equipment copper loss	4
10 MVA transformer copper loss under assumed loading conditions	1
Anode reactor voltage drop	2

DISCUSSION ON
'A HIGH-FREQUENCY SIMULATOR FOR THE ANALYSIS OF POWER SYSTEMS"*

Mr. G. Lyon (*communicated*): I believe that the paper describes important contribution to the art of network analysis. I opose to divide my comments into two parts, namely the tails of the paper and its general implications.

etails of Paper.

Owing to momentary load shedding by voltage reduction iring a disturbance, a system may resume stable operation in time-phase position relatively substantially different from its itial state. Method A is inherently capable of including this fect, whereas Method B requires a large phase range (limited the store) to do so. Was it for this reason that Method A as developed in spite of the advantages of Method B in other spects?

More details of the drifts and other inaccuracies, stated in ction 3.3.3 to be of "very tolerable proportions," would be of terest to potential users of the device.

For some years it has been customary to use the per-cent or r-unit method almost exclusively in network analyses. If this ethod had been used in the discussion of scale factors in ction 4.3, attention would have been concentrated on the base iantities appropriate to simulator design, divorced from ultiplying factors referred to power-system quantities. These ultiplying factors can vary widely, depending upon the system ing treated, without in any way affecting the design basis of e equipment. In line six of Section 4.3.3 it is surely 200 cycles the *simulator* frequency that are required.

I have been unable to think of any practical analyses of eady-state or stability conditions in which the application of a sturbance is required at a given point in the system frequency cle, referred to in Section 4.6, and in a single-phase reprentation such an application would be of doubtful validity. I ould be grateful for some enlightenment on this point.

Fig. 5A implies the use of three different networks to represent e sequence of events in the system, but in the complicated netorks encountered in practice economy of apparatus necessitates e use of the same elements for the three conditions, so that a mewhat more complicated switch would be required.

A good deal of trouble is taken in the circuit shown in Fig. 5B obtain a phase-angle indicator having a sine calibration. I el it would be better to avoid this type of calibration by using, r example, a polar indicator as employed by Robert.

It is a pity that, in using the example from the Westinghouse ectrical Transmission and Distribution Reference Book, the ithor did not refer to the current (fourth) edition,† in which e treatment is developed in per-unit terms, which are nowadays eferred. Incidentally, it should be noted that whereas parts (i) id (iii) of Figs. 7A and 7B are simplified positive-sequence netorks, part (ii) in each Figure is a simplified version of the internnected positive-, negative- and zero-sequence networks, with unt branches omitted because of the assumption of pure actances in the system. The high degree of simplification ibodied in this example does not, of course, invalidate the mparison of the two sets of results in Fig. 7D.

eneral Implications.

Starting with the minimum desirable repetition rate for a ormal cathode-ray oscillograph, the author has arrived at 10 kc/s as his design frequency for the simulator. While this is a convenient frequency for the design of the electronic equipment comprising the sources in the representation, I feel that the author has dismissed too readily the difficulty and cost of designing equipment of this frequency of a size suitable for industrial requirements. It is true that Ryder and Boast have constructed two network analysers operating at 10 kc/s, but it is clear from their writings† as well as from one's own experience of lower-frequency analysers that stray coupling difficulties are acute, and the size of the finished analyser is much the same as that of the lower-frequency equipment in more common use.

It appears that the principal equipment so far developed has been the source unit of the simulator, and it does not seem essential to construct complete system equipment for 10 kc/s to make use of the new development. On the contrary, it seems that the most fruitful application would be to replace the conventional generator units of existing a.c. network analysers by new source units of the kind described. The author himself mentions the possibility of such units working at 50 c/s. At this frequency it would no doubt be necessary to employ a different recording technique, but at the frequencies of 500 and 1 600 c/s commonly employed for network analysers, the results should be obtainable by the methods described in the paper but employing long-persistence cathode-ray tubes. For the majority of existing analysers it would be necessary to increase the output of the sources above the one watt indicated in the paper, but the increase required would be moderate.

As the author states, the conventional step-by-step methods of tackling transient stability problems are tedious, even with the customary neglect of a number of secondary factors. This is the major limitation of current designs of analyser, the second being the balancing time for large-load studies. Attempts are being made to overcome these difficulties by various methods:

(*a*) The "micronetwork" of Robert.

(*b*) Manually operated auxiliary computers.‡

(*c*) Freely suspended rotors in the angle controls with torque and inertia applied to scale mechanically.§

(*d*) Electronically controlled servo devices to make the phase-angle controls of a normal network analyser follow the angular oscillations, to an extended time-scale.

(*e*) Wholly electronic sources as described in the paper.

It is my opinion that methods (*d*) and (*e*) show most promise for future development, since they appear capable of relieving both limitations upon the analysers simultaneously and they offer the opportunity of introducing damping, excitation control, prime-mover control and other factors in a flexible manner by means of the electronic circuits. Moreover, their application is not essentially 3-phase, so that they can be applied to existing large-scale analysers without incurring the high cost of wholly new equipment. They do not, however, appear to cover saliency, an important factor in the spontaneous resynchronizing that occurs (occasionally) and can be demonstrated upon the micro-network. I should value the author's views on the prospect of

* KANEFF, S.: Paper No. 1497 M, August, 1953 (see **100**, Part II, p. 405).
† Pages 460–464.

† RYDER, J. D., and BOAST, W. B.: "Design Improvements and Operating Experience with 10-kc/s Network Analysers," *Transactions of the American I.E.E.*, 1953, 72, Part I, p. 437.
‡ JONES, K. M.: "Eight Machine Transient Stability Computor," *B.T.H. Activities*, 1950, May–June, p. 80.
§ LINSELL, R. F.: "Methods of assessing the Stability of an A.C. Power System," *Engineer*, 1951, **192**, p. 332.

including saliency, and the method he would propose to vary the machine reactance in saturation studies.

Mr. S. Kaneff (*in reply*): Fundamentally, either Method A or Method B can be used for the representation, so long as the required frequency and phase deviations respectively can be obtained. Method A was used in the initial tests because it was more readily realized with components on hand at Adelaide.

Drift and accuracy are matters controllable by circuit design, and these factors can readily be controlled to give the power-system engineer results which are more accurate than his power-system parameters, using circuit techniques of the same order of complexity as that outlined in the paper.

I agree that use of the per-unit system is an advantage.

In Section 4.3.3, the "200 cycles" can refer either to simulator or to mains frequency, because the operation discussed is the same in terms of cycles for both model and actual system.

Fault application at a given point in the power-system cycle is not of interest for stability studies, but can be important in some voltage transient studies (as is mentioned in the paper, use of the simulator is not restricted to stability investigations). It must be mentioned that fault application and measuring methods as outlined were of a very primitive nature and would be replaced in a practical simulator by more sophisticated techniques.

Serious consideration has not yet been given to the representation of saliency, beyond modification of the internal e.m.f. and reactance of the synchronous-machine model, but further work along these lines is to be done.

Varying machine reactance during saturation studies can be obtained by actually switching in values of reactance correspon ing to subtransient, transient, and synchronous reactance correct sequence, or perhaps more conveniently by using electronic circuit whose reactance varies in the correct mann dependent on the armature current.

In general I agree with Mr. Lyon's "General Implications and experience has shown that although 10 kc/s can be us successfully for operating a power-system simulator, at least a small scale, there are important considerations which sugg that a repetitive simulator making use of such high frequenci although very convenient to use, is not entirely necessary. useful application of the methods discussed in the paper is, Mr. Lyon suggests, in the conversion of existing netwo analysers to dynamic operation by changing only the generat units. In such a conversion the existing frequency of operati would be retained, and there is much to be said for use of extended time scale, such as one minute on the model equal one second in the actual system. Although this takes away t benefits of repetitive operation, much simplification can effected in equipment design and operation: for example, simp relays can be used to perform complex switching operation and pen recorders can be used for direct recording of resul The fact that such a system requires a minute or so to produ an angle/time curve, instead of the almost instantaneous resu obtainable with the repetitive method, is of not much cons quence, because by far the greater amount of time taken in a stu lies in the setting-up processes.

It is hoped to describe the conversion of an existing netwo analyser to dynamic operation in a forthcoming paper.

DIGEST OF AN INSTITUTION MONOGRAPH

THE DESIGN OF COILS FOR THE PRODUCTION OF HIGH MAGNETIC FIELDS

621.318.42 : 621.3.013 Monograph No. 102M

A. N. INCE, B.Sc.

(DIGEST *of a paper published in July, 1954, as an* INSTITUTION MONOGRAPH *and to be republished in Part C of the* PROCEEDINGS.)

Very strong transient magnetic fields may be produced by the discharge of a bank of condensers through a suitable coil. Under such conditions the instantaneous current may rise to a very high value, and the design of the coil may therefore be limited by temperature rise or by electro-mechanical forces. In the present paper it is assumed that temperature rise is the limiting factor, and curves are given to enable a determination to be made of the best size, shape and number of turns for the coil when this is the case. Consideration is also given to the modifications which must be made to the coil so designed if the electro-mechanical forces in it prove to be too great.

In many practical cases the discharge will be oscillatory with a very low Q-factor, and most of the heat will be dissipated during the first half-cycle. Alternatively, when the Q-factor is not very low, steps may be taken to prevent the flow of current after the first half-cycle so that, in either case, it is sufficient to allow only for heat generated during this half-cycle.

It is assumed that the internal radius of the coil and the duration of the first half-cycle are fixed by factors outside the control the designer, and the procedure for determining the remainin constants of the coil in terms of the capacitance and voltage the bank of condensers is then described in detail.

Mr. Ince is in the Department of Engineering, University of Cambridge.

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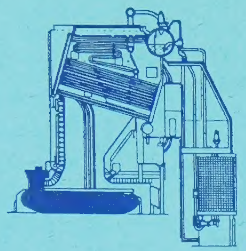

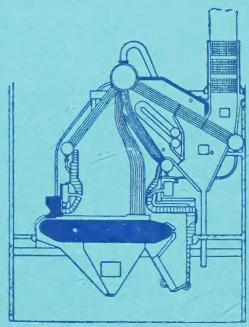

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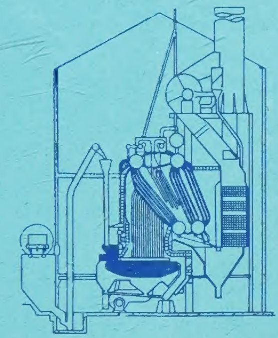

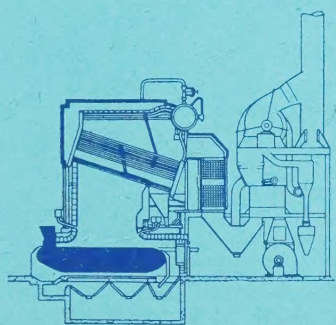

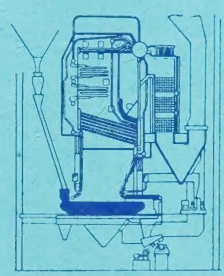

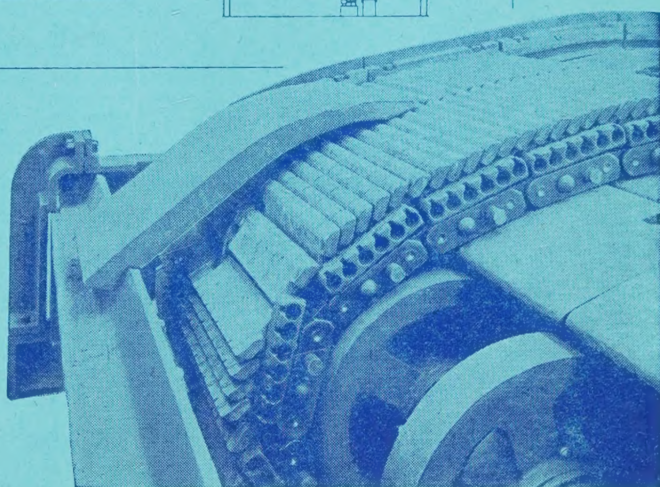

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